The secret life of boilers: Dynamic performance of residential gas boiler heating systems – a modelling and empirical study

by

George James Bennett

UCL Energy Institute

Bartlett School of Environment, Energy and Resources

Thesis submitted for the degree of Doctor of Philosophy in Energy and the Built Environment

Declaration

I, George James Bennett, confirm that the work presented in this thesis is my own. Where information has been derived from other sources or in collaboration with other researchers, I confirm that this has been indicated in the thesis.

George James Bennett

Abstract

Residential space and water heating accounts for 23% of UK final energy demand and combination gas boilers are the dominant technology. Performance gap issues in gas boiler systems have been reported, with previous studies unable to isolate or quantify root causes for performance issues. Dynamic behaviour of boiler heating systems is important to their overall performance, issues of plant size, supply temperature regulation and system control effect the performance of the system. The UK Standard Assessment Procedure (SAP), contains simplifications to aid ease of use and comparability of resulting Energy Performance Certificates (EPC) but they partly overlook these key dynamic issues.

Three complementary methods were used to analyse heating system dynamics; a cross-model comparison, real world data from four case studies and a statistical analysis of a 217 boilers sample. Comparing SAP with a dynamically modelled system, showed that SAP results correspond closely to a model using an idealistic heating system, with perfect control and instant responsiveness. Introduction of a physically realistic gas fired boiler and water-based heating system to the model results in a consistent increase in internal temperature (0.5°C) and energy demand (ca. 1000 kWh/a). Variation of controls and plant size show an efficiency penalty for oversized boilers with limited modulation and poor thermostat controls. The key issue of boiler cycling was highlighted as a dynamic symptom of poor efficiency performance. From in situ analysis of boilers, cycling behaviour was observed indicating widespread performance reduction, as was seen in simulation. Most observed combi-boilers appear oversized for space heating and despite available modulation are unable to prevent rapid on-off cycling. Per day, half of combi boilers studied average more than 50 starts and 70% of cycles average less than 10 minutes during space heating operation.

Boiler dynamic performance is not reflected in UK and EU efficiency testing standards, which assume steady state operation. The characterisation of the dynamics of gas boilers highlights issues of oversizing and excessive cycling, and reveals opportunities to improve the current building stock energy demand/emissions through better installations, EPCs, and energy labelling.

Impact statement

The findings of this thesis can have significant impact both in the current environment of gas boiler dominated heating in the UK but also contribute to a successful transition to the next generation of lower carbon heating systems. The performance gap related to boilers of 10% or more can be improved by addressing the issues investigated in the thesis. For boilers, installed now and in the near term, various stakeholders, both inside and outside academia, can take on board the findings here. Legislators should seek to adjust the framework around domestic heating to encourage installations that reduce the performance penalty currently seen, by targeting plant size ratios both in installation guidelines and energy performance measures. EPCs can have more impact by integrating factors which account for boiler heating system parameters which this thesis has shown to affect efficiency and emissions. By showing that not all installations of a given boiler are equal in terms of sizing and efficiency then awareness can be raised among homeowners, installers and government. In the light of linking start up behaviour with decreased efficiency and increased emission of unburnt hydrocarbons, then efficiency testing methods could be improved to include dynamic behaviour of boilers rather than the current steady state model. This could have great impact in highlighting the differences in boiler types beyond their current idealised operation, changing the perception of customers and professionals alike as well as incentivising manufacturers to address the issues at hand.

Industrial stakeholders, such as boiler and control manufacturers, can develop boiler models with wider modulation ranges to avoid cycling due to building heat demand below the boiler minimum power output, this would be especially relevant for combi boilers. Appliance software could be adapted to avoid unnecessary cycling in cases where oversizing and poor controls conspire to drive cycling behaviour. The efficiency and emission benefits of better controls can be better quantified in the light of the results shown in this thesis, by utilising not only the better field data but also more detailed dynamic modelling.

Academics can build on the findings of this thesis through dynamic building simulation which includes detailed modelling of the heating system dynamics to avoid pitfalls arising from simplifications of heating system behaviour. Deeper insight by researchers can be gained in future by utilising the methods of data collection which have exploited recent developments in internet connected appliances with direct access to internal diagnostic measurements. This, in turn, can have impact of deepening the understanding of heating systems within the energy demand research community by laying bare the complexity of such systems and raising awareness of the pitfalls of black box thinking with regards to heating appliances.

Looking forward, the issues explored in this thesis are not only relevant to boilers but also heat pumps and future heating systems. Finite modulation range, plant size ratio, emitter sizing and control of power and central heating water temperature are all factors in determining the efficiency in a wide range of heating appliances and therefore the findings here will have an impact in residential heating energy demand for many more years.

Acknowledgements

The journey to this point has been long and an experience not to be forgotten, many people helped and supported me along the way. A few words here cannot do justice to the support that was afforded to me by my academic supervisors, Prof Bob Lowe, Prof Tadj Oreszczyn and Dr Cliff Elwell. They helped guide me down the rabbit hole I entered almost 4 years ago and I thank them for their encouragement, insight and intellectually challenging support. Without them I would not have emerged from Wonderland both wiser and more curious.

Great thanks to my colleagues at Bosch Thermotechnology, both during and before embarking on this research. Thanks to Bosch for financially supporting me during my PhD, but special mention to the colleagues who supported me intellectually, suffering my endless questions and interruptions. Most notably thanks to Richard Miles, Tom Collins, Richard Forrester, Hermann Stumpp as well as Sungbae Park and Uwe Limbeck for your encouraging supervision throughout.

Thanks to all my friends and family who have suffered my interminably tedious chats about all things boiler and energy demand, but also my apologies for the conversations that will continue for years to come.

Thanks to my indomitably patient wife, Şafak, without whom I would most certainly have lost my way and possibly have gone quite mad while on this PhD quest. Her steady word, encouragement and enduring perspective were invaluable throughout the good days and the not so good.

Nomenclature

Designation/ Abbreviation	Description
ASHP	Air Source Heat Pump
BEIS	Department for Business, Energy and Industrial Strategy
BRE	Building Research Establishment
BS	British Standard
BTSL	Building Technology Simulation Library
CH	Central Heating
CHP mCHP	Combined Heat and Power Micro Combined Heat and Power
CHM	Cambridge Housing Model
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COP	Coefficient of Performance
Combi	Combination boiler, providing hot water and heating
CSV	Comma Separated Values
DE	Germany/Deutschland
DECC	Department of Energy and Climate Change
DHW	Domestic Hot Water
DIN	Deutsches Institut für Normung (German Standards Institute)
EHS	English Housing Survey
EMS	Energy Management System
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EU	European Union
GCV	Gross Calorific Value
GWP	Global Warming Potential
HEED	Health Economic Evaluations Database
HLC	Heat Loss Coefficient
HLP	Heat Loss Parameter
HMI	Human Machine Interface
HP	Heat Pump
HVAC	Heating Ventilation and Air Conditioning
IP	Internet Protocol

GSHP	Ground Source Heat Pump
MCS	Microgeneration Certification Scheme
MIT	Mean Internal Temperature
NCM	National Calculation Method
NCV	Net Calorific Value
PRISM	PRInceton Scorekeeping Method
PSR	Plant Size Ratio
PTG	Power Temperature Gradient
RMHB_DE	Terraced house, unrenovated, Germany (virtual house in BTSL) (ReihenMittelHausBestand_Deutschland)
RMHN_DE	Terraced house, renovated, Germany (virtual house in BTSL) (ReihenMittelHausNeu_Deutschland)
RMHB_GB	Terraced house, unrenovated, UK (virtual house in BTSL) (ReihenMittelHausBestand_GrossBrittanien)
RMHN_GB	Terraced house, renovated, UK (virtual house in BTSL) (ReihenMittelHausNeu_GrossBrittanien)
SAP	Standard Assessment Procedure
SPF	Seasonal Performance Factor
TFA	Total Floor Area
THC	Total Hydrocarbon
TMP	Thermal Mass Parameter
Tapping	Hot water demand
UK	United Kingdom

Table of Contents

Table of figures

About the author

As an employee of Bosch Thermotechnology since 2007 I have had experience from the heating equipment manufacturer point of view before commencing this PhD as part of the Bosch sponsored PhD program. Previous to and during this PhD project I was resident in Germany, as such I am fluent in German and any references to German standards, reports or literature have been read by myself in the original.

1 Introduction

The large and complex field of energy demand in the 21st century and its impact on our environment covers issues from the grand global scale to the personal and seemingly mundane. The global challenge of meeting climate change targets set out in agreements such as Kyoto (1997) and Paris (IISD, 2015) has been taken up at international and national levels with targets to achieve greenhouse gas emission reductions with a view to avoiding catastrophic global warming. Within the European Union, the EU 2030 emissions reduction target is 40% (EC, 2014), achieving this target in the EU member states requires breaking down the top-level goals into effective and, above all, implementable actions across 28 sovereign member states[1]. Negotiating a way through the complex interplay of energy supply and demand as well as the labyrinth of legislation which governs and restricts these areas is a huge challenge in itself (Pérez-Lombard et al., 2009).

One sector which contributes significantly to overall energy usage is that of residential energy demand. Protection from the elements and the provision of a safe and healthy environment for humans are fundamental tenets of what it means to have a residence since the earliest days of cave dwellings (Sørensen, 2009); ever since humans started to build their own dwellings focus has always been laid, among many other aspects, on making the structures as comfortable as possible within the constraints of the time. In modern times this has led to trends which attempt to balance the need for comfort with the financial and environmental cost of energy consumption. At a basic level the interaction of human, building and technology and the compromises necessary to address this multifaceted problem in millions of buildings every day has presented researchers, technologists and legislators with a tantalising socio-technical riddle. Residential energy demand accounts for roughly 1/3 of energy usage across the European Union (EUROSTAT, 2013) and heating energy is a major contributor, in terms of both space heating and hot water heating. Specifically, in the UK residential energy demand accounts for 29% national final energy (BEIS, 2017b) thereof 80% coming from space and water heating.

One technology dominates the residential heating landscape in the UK, the gas boiler. In 2007 boilers accounted for 86% of the heating systems of England (DCLG, 2007). As

---

[1] This thesis spans the EU referendum of 2015 in the UK and due to the uncertainty of 'Brexit' on EU law in the UK the research has been conducted from the viewpoint of UK membership in the EU and the continued adherence to relevant EU legislation, as was the case at the beginning of the project.

the leading technology, heating systems with gas boilers, have a major impact on the carbon emissions of the country and the fuel bills of occupants. Small improvements in the performance of gas boiler heating could have a major impact and since a performance gap between predicted and actual energy demand has been identified in this area (Orr et al., 2009, Hayton, 2009, Wolff et al., 2004) research in this area is still warranted.

The aim of the research is to explore the possible improvement of UK heating system performance by exploring the dynamic behaviour of boiler heating systems and consequently their efficiency. By addressing the following objectives, a contribution to closing the performance gap for boiler-based heating systems can be made.

- Quantifying the influence of boiler oversizing on dynamic behaviour and system efficiency for space heating in a simulation environment.
- Exploring the ability of system controllers to mitigate any negative effects of boiler oversizing.
- Identify poor dynamic behaviour of boilers in situ in the context of simulation results.
- Through case study analysis deepen understanding of the causes and symptoms of boiler dynamic behaviour.
- Explore ways in which the regulatory tools could be improved to incentivise better boiler heating systems.
- Explore ways in which heating systems can be improved in practice, without compromising customer perception or cost, and can be made ready for next generation heat sources.

The research undertaken in this thesis will focus on addressing the performance gap issues attributable to gas boiler based residential heating systems. By modelling, with intimate dynamic detail of the heating system and through monitoring of boilers in a new level of detail this thesis will shed new light onto theoretical and practical aspects of this subset of the global environmental challenge while still treading carefully through the commonplace complexities of the energy use in such buildings as we live in. New measurement techniques are needed to provide the quality of data needed for a deep analysis of the fine temporal cycling behaviour of boilers. Access to boiler diagnostic data in modern heating appliances allows for recording of high frequency data for a fraction of the cost and effort compared to traditional methods. Remote logging has also allowed low cost recording of data from many locations simultaneously, thus allowing higher levels of detail than previous studies and greater insight. With modern data acquisition tools and an appreciation for heating system dynamic operation and control, insights can be gained which can contribute to further improving gas boiler-based heating system performance.

Mixed methods and data sources will be used to tackle the challenges at hand. Simulation of various heating system configurations in a detailed and dynamic manner, will be complemented by case studies and high frequency boiler diagnostic data to provide insights into this dominant technology in new ways. The aim is to contribute to the technology's operational capability through improved boiler installations, appliances, systems and controls. Energy Performance Certificates may also benefit from the findings by improved ranking of heating systems thereby incentivising the market and driving change. Future heating systems can benefit by learning from the weaknesses and strengths of the current leading heating technology and avoid repeating or prolonging the failures of today.

2 Literature Review

Against the backdrop of global carbon reduction, clarity is needed to make sense of energy demand in the residential space, with a view to understanding, estimating and reducing energy consumption. The road to reducing energy demand has proven to be a complex interaction of many fields of knowledge, skills and disciplines. This section will review the accumulated knowledge and developments in the field of building physics including domestic heating systems, taking a deeper look into the peculiarities of the residential sector. It will then address aspects of human behaviour as manifested through heating and hot water demand. Finally, historical, state of the art and future heating systems will be discussed followed by the use of building simulation and its role in standardisation and legislation.

Although many advances have been made in technology, legislation and a great deal of knowledge of building thermal behaviour has been gathered over the years, the so-called 'performance gap', the difference between designed and as-built performance (Johnston et al., 2015, de Wilde, 2014, Menezes et al., 2012, ZCH, 2014), continues to recur in energy assessment (Bordass et al., 2001) of both new and refurbished buildings. The following sections cover topics which are not only fundamental to the topic of accurate building energy performance prediction but have also, to greater or lesser extent, been associated with the issue of performance gap. A convenient and common categorisation of the topics contributing to building energy performance (and the associated performance gap) are, occupants, heating system and building fabric, as such the following sections will follow the same general distinctions. It is to be borne in mind that these factors are diverse and varied, and the length or depth of discussion in this thesis does not represent their comparative contribution in reality, which is under active investigation by other researchers.

The division of topics for the purpose of outlining the components of the building energy system in this thesis differs somewhat to the analysis of performance gap. Research on understanding performance gap looks closely at the mechanisms leading to a mismatch between predicted and actual energy consumption. Essentially the mechanisms fall into 4 broad categories:

- Technical components such as heating systems not performing as expected (Orr et al., 2009, EST, 2010, Bourke et al., 2014).
- Incorrect predictions from models (Crawley et al., 2008, Kokogiannakis et al., 2008).
- Incorrect representation of physical mechanism within models (Lowe et al., 2007).

- Socio-technical, real world interactions of building, heating system and occupant gives unexpected outcomes, which can be misdiagnosed when categorised as 'irrational' occupant behaviour or customer misuse (Lowe et al., 2017c, Chiu et al., 2014).

Although the performance gap is a multi-faceted problem, it is the issue of the technical heating system that will be the focus of the literature review to follow. As will be seen, this does not limit the topic to just the technical system, many topics influence and complement the technical issue of heating system performance. Therefore, in the following sections, more detail will be given regarding the main themes and contradictions making up the problems in the residential heating sector pertaining to the systems that deliver the heat. To move forward in this area technical issues with design, selection and implementation of heating systems will be reviewed covering the topics of building physics simulation, occupant driven demand, heating system componentry and design as well as the methods and standards used for selection, benchmarking and legislation of heating systems. The review will cover research in the field and the efforts of legislators, homeowners and industry to achieve their often-competing goals and the resulting effect on heating energy consumption in the built environment. The aim being to identify gaps, bias and cases where knowledge has not kept pace with ever changing reality in this field.

2.1 Building Physics and the Energy System

A building as a living or working space requires energy to perform its purpose whether it be Neanderthals cooking in caves (Sørensen, 2009), traditional factories, schools, hospitals, flats, houses or data centres managing internet dataflow (Lent, 2016). As such, efforts have been made to understand the energy flow into and inevitably back out of the building in operation. To say that building physics is only a matter of energy optimisation would be a significant over simplification. Building physics has at its core a multi parameter system that must understand and balance contradictory priorities. Taken one-step towards its absurd conclusion, the most energy efficient building could be an airtight box with no windows, which is before considering even more seemingly absurd technical energy efficiency solutions such as zero air exchange or minimal external surface area. Clearly pure technical consideration of energy efficiency issues would render buildings unsuitable for human inhabitation, therefore underlining the fundamentally socio-technical nature of the problem.

In order to begin to grapple with problem of building energy demand in practice a firm foundation is necessary, an understanding of the physics of buildings and their energy systems is fundamental to predicting the energy consumption of both new buildings and refurbishment projects in the design phase before committing major financial and physical resources. Building design professionals (architects, building system engineers, heating system designers etc.) may need to prove at the design stage that the building will meet certain minimum energy efficiency standards (DCLG, 2010), while balancing other monetary factors and their effect on market value. What constitutes a 'green' building has become better defined over the years with a number of standards such as LEED, Passivhaus and BREEAM setting internationally recognised benchmarks. Although these standards are not without controversy, with the inability to predict eventual real energy demand prompting legal action (Hughes, 2011). But these high efficiency buildings represent a specialised segment of the market whereas the improvement of the wider building stock is covered by the continually evolving building regulations and financial incentives. The quality of the indoor environment is also an important consideration in the planning of buildings. This can take the form of air quality, thermal comfort or the propensity for summer overheating, all of which can lead to contradictory design choices when considered alongside energy efficiency. Nevertheless, the role of energy performance prediction at the design stage continues to be of great interest and importance, forming a key component of building regulation compliance, especially in the area of building energy labelling and certification as will be elaborated upon in the following sections.

2.2 Occupant driven demand

Heating systems in buildings are there to perform the function of meeting the space heating and hot water requirements of the inhabitants of the building. Understanding what these requirements are and how they are formed transforms consideration of the issues into a socio-technical problem. Since the 1980s considerable effort has been invested in research contributing to understanding the social technical issues in building energy efficiency and the field continues to be a popular area of research (Lowe et al., 2017c).

The occupants of any dwelling are integral to the way that the building energy system operates; their behaviour, whether it be passive or active, conscious or unconscious, drives the overall energy demand. Many empirical and epidemiological studies have been carried out to understand how occupant behaviour is manifesting itself in UK buildings. Studies of internal temperatures have a long history, with examples dating back to the 1950s (Danter, 1951). The history of measurements of internal temperatures (Vadodaria et al., 2014) alludes to other influencing factors or perhaps a temporal evolving of the internal temperatures (Uglow, 1981) associated with an approximate 1°C internal temperature increase per decade. Studies of energy demand patterns (DECC, 2014) have gathered data from gas/electric meters, temperature sensors and questionnaires. Invaluable insights have been gained into how occupant behaviour is manifested in terms of energy demand and environment.

By monitoring temperatures and behaviours inside homes researchers have measured the temperature levels in dwellings (Huebner et al., 2013a, Huebner et al., 2013b, Shipworth et al., 2010), from which a probable schedule of the heating systems can be implied. Empirical data is crucial in understanding occupant behaviour and its driving role in energy demand, and feeding back into the models used to predict consumption levels in buildings on an individual and national scale (Hughes et al., 2016). Effort needs to be continually reinvested in this area to keep up to date with current behavioural trends, technological changes and to elaborate on existing knowledge with additional disaggregated information to further understanding in this area, for example with hot water use or individual electrical appliances. Underlying the study of occupant behaviour, as expressed through thermostat settings and internal temperatures is our complex biophysical relationship with temperature (Fiala et al., 1999, Kingma et al., 2014, Schweiker et al., 2017) and this should be considered also in the residential energy demand research.

2.2.1 Room temperature & heating patterns

Heating systems are programmed based on a heating schedule which acts as a proxy for the thermal comfort requirements of the occupants, the range and basic influencing parameters are important to be understood in order to interpret the dynamic behaviour of the temperature that will be encountered later.

Research is extensive in the area of thermal comfort looking at many aspects such as the sociological and qualitative influences on the perception of thermal comfort as the driver of energy demand and has consistently found over many decades that for the same building types such factors can combine into a wide variation in energy consumption in a seemingly homogeneous socio-technical group (Gram-Hanssen, 2010, Pickup and Miles, 1977a). Modelling of the resulting thermal strain on the human body, with simplified physiology, has been researched with a view to understanding the perceived thermal sensation on the human body through the complex interaction of both surface heat loss and internal heat flows across the multitude of body tissue types.

Thermal comfort is defined as ‘*that condition of mind which expresses satisfaction with the thermal environment*’ (BSI, 2006) and it remains to convert this concept in to physical quantities which can be measured and regulated in the service of human thermal comfort. The parameters which influence the perceived temperature felt by a person in a room are many and varied, so simplifications are prevalent in the conceptual framework supporting knowledge of human thermal comfort. Many parameters influence the thermal comfort of an individual, four external physical factors are (Taleghani et al., 2013):

- Air Temperature
- Radiative Temperature
- Air speed
- Relative Humidity

Which need to be taken into consideration in conjunction with personal factors:

- Clothing insulation
- Metabolic heat

The following text summarises the current state of understanding of thermal comfort; however, historical factors are not included, and it excludes any consideration of economic factors such as price sensitivity and energy costs/income comparisons.

Although research continues in the area of thermal comfort, notably the upcoming *IEA-EBC Annex 69: Strategy and practice of adaptive thermal comfort in low energy buildings* , there are currently two common standards for calculation of comfort temperature exist: ASHRAE 55-2010 (ANSI, 2013) and EN15251:2007. Both are based on the work of Fanger (Fanger, 1972) which includes body, heat storage, metabolism, work, heat exchange (radiative, conductive, convective and evaporative) and finally heat loss by respiration. Crucially the standards make use of the field observed dependency of thermal comfort impression on recent outdoor temperature in the form of a weighted running average. This means that, although the standards share a common methodological history the factors used vary and the resulting comfort temperatures also. In the case of ASHRAE 55 this leads to an adaptive internal comfort temperature shown in Figure 1.

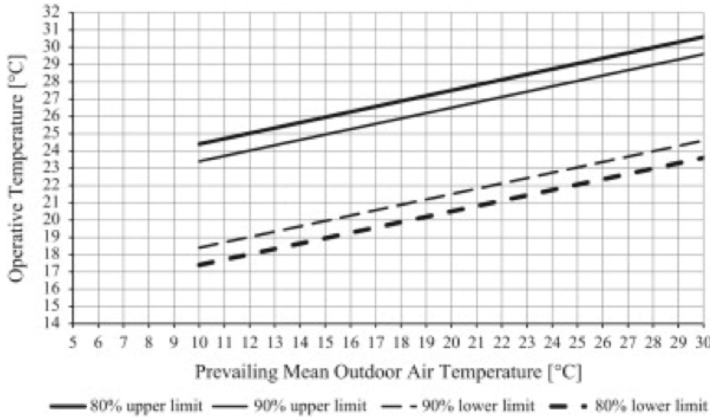


Figure 1: Comfort bandwidths of ASHRAE 55-2010

The comfort temperature from the equivalent European norm, EN 15251, is based on a similar relationship with outdoor temperature but with minimum and maximum boundaries of allowable indoor temperature at the lower and higher outdoor temperatures.

For the purposes of analysing the performance of the heating system there is no requirement to dive too deep into the topic of thermal comfort therefore it will be treated appropriately in the analysis. Thermal comfort, from the point of view of the heating system, is based on the physical parameters has been considered in such a way that these factors can partly be combined into one representative temperature, namely the operational temperature, a concept dating back to the mid of the 20th century (Winslow, 1949).

In a hypothetical room where the energy exchange between the person and the surroundings is equal, where air speeds are low and the walls have unity emissivity then the operative temperature is defined as:

$$T_o = AT_a + (1 - A)T_r$$

Equation 1 (Butcher et al., 2015)

Where T_o is operative temperature, T_a is air temperature and T_r is mean radiant temperature. For airspeed $v_{a\,(m/s)}$:

$$v_a < 0.2: \quad A = 0.5$$
$$0.2 < v_a < 0.6: \quad A = 0.6$$
$$0.6 < v_a < 1.0: \quad A = 0.7$$

According to the CIBSE guide A (Butcher et al., 2015) in most practical cases where the air speed is low and the mean air/radiant temperature difference is also low, then the operative temperature can be taken as the average of air temperature and mean radiant temperature from the surrounding building structure.

$$T_o = \tfrac{1}{2}T_a + \tfrac{1}{2}T_r$$

Equation 2

Where T_o is operative temperature, T_a is air temperature and T_r is mean radiant temperature.

Using such quantitative physical equations leads to charts which can be used as a guide to the perceived thermal comfort based on operative temperature and humidity. For the purpose of heating system control, this is where the story of comfort ends. Modern room controllers which determine if a heat input is necessary generally measure a mixture of air and radiative wall temperature (assuming the installation instructions are followed (Bosch, 2018a)) which doubles as a proxy for occupant comfort with manual adjustment to achieve satisfactory comfort at any given time.

Temperature rises have been recorded in buildings after retrofit activities and had generally been assumed to be subject to ‘thermal takeback’ or ‘rebound’ which occurs when occupants take thermal efficiency savings partly as energy savings and partly as an increase in thermal comfort (Greening et al., 2000, Hirst et al., 1985). This concept of altered behaviour as post efficiency improvement has been further expanded by better considering the conditions before interventions took place, thereby defining ‘prebound’ (Sunikka-Blank and Galvin, 2012) where less energy is used before retrofit than predicted. However, it has also often been shown that maintaining the same heating pattern will result in an increase in mean temperature, both by using simple energy balance calculations (Uglow, 1981) and modern simulation tools (Deurinck et al., 2012), implying that the occupant instigated takeback may be less than expected.

2.2.2 Domestic Hot water

Domestic Hot Water (DHW) demand is generally accepted to be predominantly proportional to the number of occupants residing in a dwelling (Shorrock, 2009, EST, 2008), with factors such as heater type, region and type of occupant not considered significant factors. As such, simplifications of this relationship, which black box the complexity of human behaviour, have been implemented in national standards, like SAP, where occupancy can be linked to floor area (DECC, 2012). However, research continues to quantify and draw attention to the underlying influencing parameters of DHW consumption and attempt to incorporate issues such as user behaviour into standards and public information channels like Energy Performance Certificates (Hunt and Rogers, 2014).

Delivery temperature of DHW is between 40°C and 60°C (EST, 2008) and there is a seasonal variation in the cold water supply temperature (EST, 2008) which will unavoidably impact on heat energy required for DHW preparation. Whereas space heating demand can be reduced by improving the efficiency of heat production, the level of occupant demand (i.e. setpoint temperature) and building heat loss, the scope is less with DHW. Volume, flow rate and temperature rise determine the energy need and it should be delivered as efficiently as possible, so without change in occupant behaviour to reduce the volume or temperature then this lower limit is not likely to be crossed. How the hot water is heated can be improved to reduce reliance on primary fuel sources by implementing solar thermal or heat pumps. The trend in DHW legislation has been to stipulate improvement to the efficiency of production through improvements in boilers and other hot water heaters or through subsidies for solar water heating. Although this has improved the efficiency situation for DHW supply, demand side reduction is more challenging.

To demonstrate the relative magnitude of energy consumption for hot water and space heating, Energy Savings Trust found an average of 4.6 kWh/day (±0.6) (EST, 2008) for DHW whereas the median total gas consumption (including space heating, hot water and cooking) in the EFUS (DECC, 2014) study have a space heating requirement of more than 40.2 kWh/day (equivalent to 14700kWh per annum).

2.2.3 Socio-technical nexus

In recent years, research has increased in response to the realisation that these two subjects cannot be treated in isolation. The socio-technical nature of this interaction and the challenges it presents have gained momentum in academic literature (Chiu et al., 2014, Lowe et al., 2017c). The interaction of users and technical systems has been recognised as a complex issue where the expected behaviour assumed during technology development is rarely seen in practice. Issues such as misunderstandings of the way technologies function, seemingly (at least from the superficial perspective of external observers) irrational thermal preferences and conflicting use of thermal equipment will all lead to unexpected thermal energy demand.

Although this is certainly an important aspect of residential thermal energy demand this thesis will focus in the main on technical issues regarding heating systems, their thermodynamic behaviour and interaction with the buildings in which they operate. The wider sociological context of heating and how technical systems and their users interact will not be considered in depth but will be kept in view while analysing, discussing and drawing conclusions from the data collected

2.3 Heating Technologies

2.3.1 Domestic Central Heating Systems

Modern domestic central heating systems come in many shapes and forms and are, much like the buildings in which they are installed, evolving with time (Brand, 1997). However, the archetypes on which all these systems are based, have common features which can be used to categorise heating systems and the heating appliances required to drive them.

The defining feature of a 'central' heating system is that the conversion from energy delivered into heat takes place in one primary centralised place and is then distributed through the building via a hydronic (Hansen, 1985) or air based network in order to transfer heat to the various living spaces either as space heating or domestic hot water. The heat source can be in or at the building itself or remote as in the case of district heating systems. Besides the heat source, which will be elaborated upon in the next section the layout of the hydronic distribution forms a major distinguishing feature of central heating systems. Figure 2 to Figure 8 show common types of heating system in the UK; red lines indicate hot water flow from the heat source, and blue shows the cooler return water coming back to the heat source after transferring heat via the emitters (radiators, underfloor heating etc.) to the living spaces; the water is then heated again and circulated back through the heating circuit. The systems are depicted with gas boilers for simplicity at this stage; further explanation of the different types of heat sources comes in the next section. The broad categories depicted by no means describe all possible heating system configurations but do provide a convenient framework for describing the basic functional principles of different residential heating systems. One way in which a category could be modified from the stereotypes is through heat emitter choice in the living space of the buildings which is also depicted here consistently as wall mounted radiators. Different emitter types, primarily with regards to size and temperature can be used; their effect on the system behaviour will be described later.

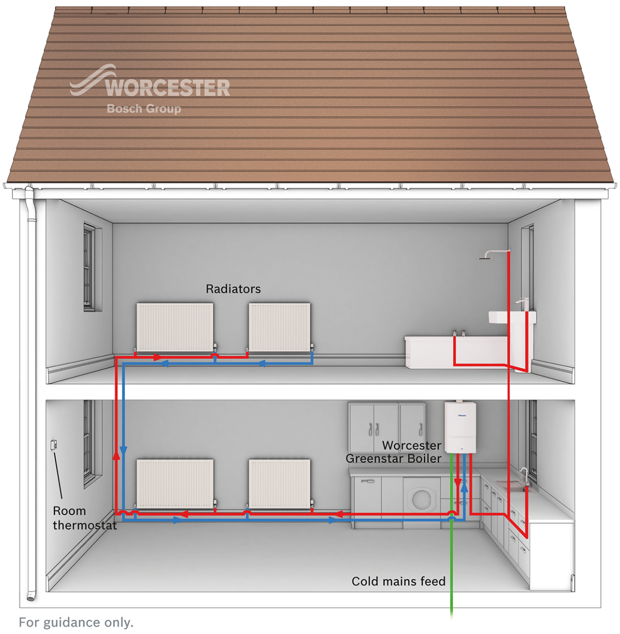


Figure 2: Combi boiler heating & hot water system (Bosch, 2018d)[2]

[2] System diagram image copyright Bosch Thermotechnology, reproduced here with permission

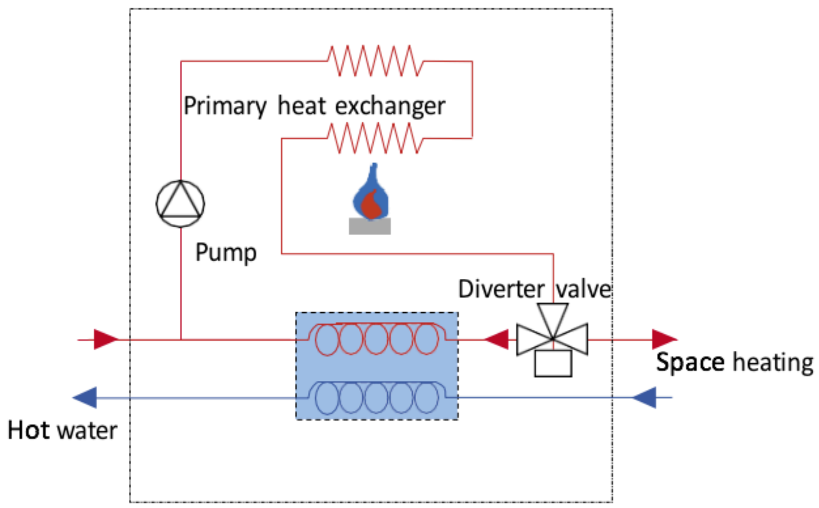


Figure 3: Combi boiler internal circuit and component schematic

In a so-called combination boiler system, as shown in Figure 2/Figure 3, although simple from the layout of the hydronic system, the complexity lies in the internal design of the boiler itself which needs to manage the switching of heat transfer, and therewith also temperature and flow rates, to the heating or hot water network.

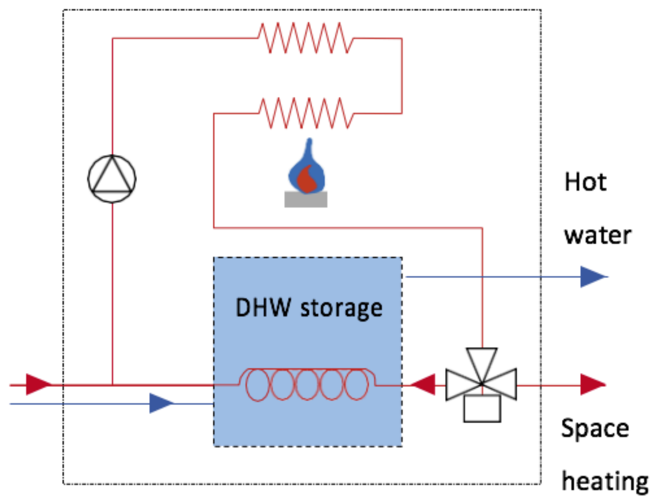


Figure 4: Combi boiler with internal hot water storage

Although a combination boiler can have a small hot water storage within the appliance (Bosch, 2015b) (as per the variant shown in Figure 4), generally the benefit lies in its compact space saving design and simple installation which is predicated on not having a large storage facility and instantaneous/on demand hot water production. The drawback is that the hot water supply, temperature and flow rate (even in the case of those combi appliances with a small storage) is limited by the heat transfer ability from the system water to the incoming cold water during the instantaneous hot water production. For example, a combi boiler rated at 25kW can continuously produce

10.2l/min at a temperature rise of 35K (i.e. 45°C outlet temperature from 10°C mains cold water), equivalent to approximately two simultaneous showers. In cases where the building simultaneous hot water demand can exceed these levels then either a larger thermal output combi, hot water storage or buffer is normally specified. The benefit of a compact appliance through rationalising space and hot water heating into one device provides an engineering trade-off for the designers; although the hot water delivery rate can be calculated simply as above, and thereby the required thermal output to satisfy the hot water requirement, this must be balanced against the expected space heating requirement. This level of detail would only be a first approximation and capability of the system as a whole must be considered, the specifics of the components which must be carefully selected to provide the required demand in a gas boiler will be explained in section 2.3.3. It is worth noting how hot water demand from the point of view of a combination boiler specification differs from the way DHW demand is specified in national standards and calculation methods (see section 2.2.2 and 2.6).

Thermal storage may be desirable in the installation for the purpose of providing a storage and buffer mechanism between heat producer and user; this can be for reasons mentioned above, in order to allow a more flexible hot water delivery envelope or to act as a buffer between heat sources such as solar thermal, which cannot operate on demand. The heating system shown in Figure 5 shows a common standard for a heating system with a hot water storage tank, which shares an important trait with the combi system already described in that the hydronic system is sealed and pressurised. The water in the central heating circuit (i.e. boiler -> tank -> emitters -> boiler) is filled using mains water, often with the addition of anti-corrosion additives or through a deionisation filter, to a pressure of 1.5-2.5bar (gauge) and then closed from the mains feed water. Sealing the system provides the benefit of a hydronic system pressure higher than atmospheric which enables, through an increase in boiling temperature of the system water, a higher thermal robustness of the heating system. Safety is enhanced by pushing the boiling temperature significantly outside the normal temperature operating range of the heater/boiler. However, even remaining below the boiling temperature of water under these higher pressures, expansion of the water during heating operation will result in a rapid increase in system pressure if no measure is taken. Expansion vessels, sized for the volume and temperature rise, are installed in the sealed system to allow expansion space. The construction of such an expansion vessel normally takes the form of a pressure vessel containing a volume of nitrogen separated from the system water via a flexible rubber membrane, thus allowing the water to expand into the gaseous expansion space in a repeatable manner. Additionally, the sealed nature of these systems allows for a more controlled corrosion environment, with the initial conditions during filling playing a crucial role in the total corrosion potential, but also limiting corrosion through limited addition of oxygen in the heating system lifetime.

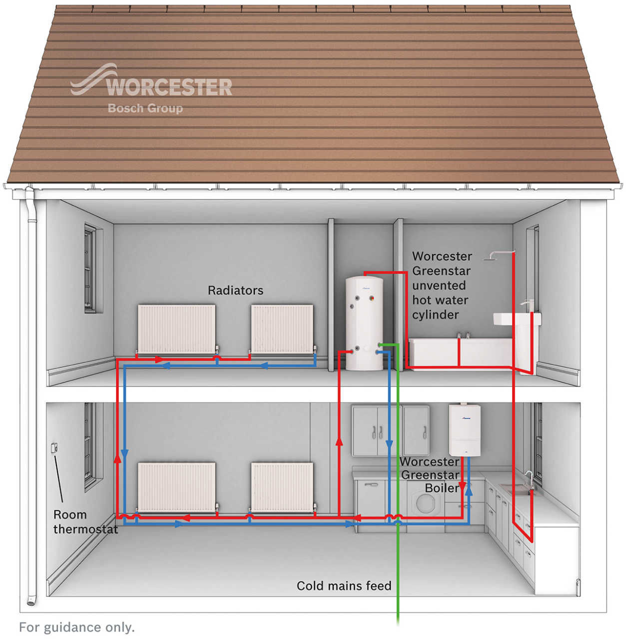


Figure 5: System boiler with storage tank (sealed system) (Bosch, 2018d)

Prior to the advent of sealed system hydraulics, heating system water was fed from a tank installed at the highest point in the circuit to enable system pressurisation through simple gravitational head of water (see Figure 6). The system pressure would be determined by the height of the header tank, and the expansion of the heating water would be accommodated by the tank itself and its openness to atmosphere. Such a system was relatively simple in operation but, when compared to sealed systems, had the drawback of limited pressure and therefore maximum operating temperature and susceptibility to corrosion. The historical development of heating systems and market pressure driving the trend for more compact systems has meant that open/gravity fed systems are reducing in number (DCLG, 2017), being replaced either by sealed system combis or system boilers both of which will give a net space saving to the home owner.

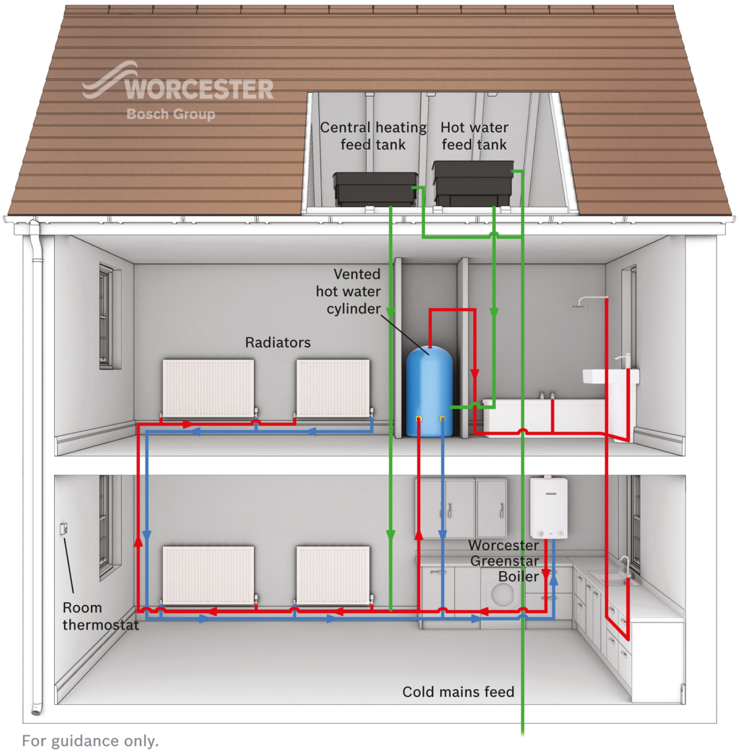


Figure 6: Regular boiler with storage tank (open/gravity system) (Bosch, 2018d)

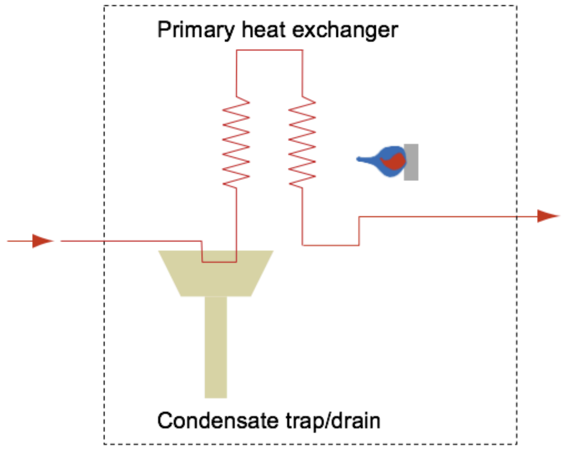
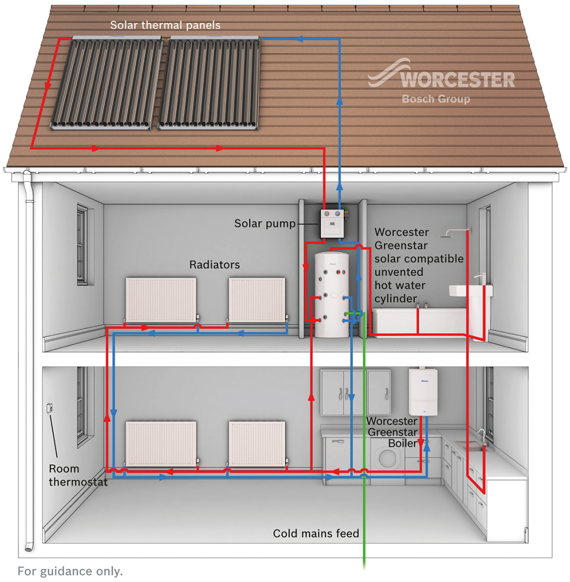


Figure 7: System/regular boiler internal schematic

The inclusion of hot water storage in the system means that it becomes feasible to install additional heat sources becomes feasible. In Figure 8 a system is shown where the hot water tank is not only heated by the boiler but also a roof mounted thermal solar panel system. The secondary heat source can take many forms, from solar thermal to heat pumps or wood stoves. Not only can the type of secondary heat source vary considerably but the heating system in its totality is rarely the same from building to building, only the main archetypes have been described here. However, as will be shown later, although the permutations of heating system are almost endless the UK market is heavily biased towards relatively simple combination boiler type.



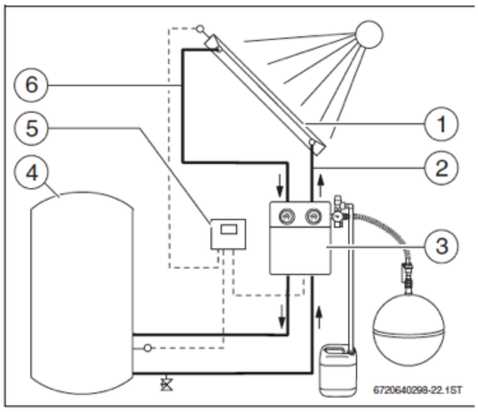


Fig. 2 *Solar thermal system components*

1 Collector with collector sensor at the top
2 Pipework (return)
3 Solar pump station with expansion vessel, temperature and safety equipment
4 Solar cylinder
5 Solar controller
6 Pipework (flow)

Figure 8: System boiler with solar heating and dual coil storage tank (sealed system)(Bosch, 2018d)

Within basic types of heating system described both the heat source and the heat emitter can take different forms. The emitter size can be varied in order to achieve the required heat transfer and temperature drop across the emitter (Butcher et al., 2015), which has already been proven both in theory and practice to have a significant effect on system efficiency where gas boilers are installed (Wolff et al., 2004, Orr et al., 2009) through mechanisms such as mismatched heater and emitter, which will be described further in the next section.

2.3.2 Heat system sizing

An important aspect of the design of a heating system in any building, besides the topics covered in the previous section, is the thermal output of the heat source. This should be chosen in such a way as to be appropriate for the building in which it will operate and the emitter network it is connected to.

Heating system design and sizing (both in terms of heat source and heat emitters) is a process that can be calculated based on relatively simple criteria and methods such as those published by CIBSE (Butcher, 2005) which take into consideration the coldest expected day, the desired internal temperature and the heat loss of the building. The technical steps of predicting the building heat loss start with the so-called 'design day' which represents the coldest expected outdoor air temperature. Using the design day external temperature, the desired indoor temperature and the assumed building heat loss then the thermal power required to maintain the equilibrium can be calculated accordingly:

$$\dot{Q}_B = \sum (UA\Delta\text{T}) + C_v\Delta T$$

Equation 3: Building space heat loss for plant size calculation (Butcher et al., 2015)

$$Where\ \dot{Q}_B = \text{rate of } building\ steady\ state\ heat\ loss\ (W),$$
$$U = heat\ transfer\ coefficient\ or\ thermal\ transmittance\ (W/m^2\,K),$$
$$A = Building\ element\ area\ (m^2),\ \ \Delta T = design\ temperature\ difference\ (K),$$
$$C_v = ventilation\ coefficient\ (W/K)$$

However, steady state maintenance of an internal temperature is only part of the requirement of a heating system. If the building internal temperature was to be maintained continuously then the power output derived from Equation 3 would suffice, but heating systems are often required to operate intermittently due to occupancy, comfort requirements or tradition (Huebner et al., 2013b).

It is possible to adjust the heat loss to account for the dynamic operation of the heating system, and thermal properties of the dwelling, based on complex or simple models of system performance. A simple empirical estimate (Equation 4) of the required heater power may be obtained by applying the steady state building heat loss based on the number of hours per day that the heating system is inactive and the thermal time constant of the building.

$$\dot{Q}_H = \dot{Q}_B\left(\frac{t_{0\prime}}{t_{eq}} + 1\right)$$

Equation 4

(Buderus-Heiztechnik GmbH, 2002)(Ch. 3)

$$Where\ \dot{Q}_H = heater\ power\ (W),\ \dot{Q}_B = building\ steady\ state\ heat\ loss\ (W),$$
$$t_{0\prime} = OFF\ time\ of\ heating\ in\ a\ 24\ hour\ period\ (h),$$
$$t_{eq} = time\ for\ building\ to\ reach\ thermal\ equilibrium\ (h)$$

The responsible person for specifying the heating system could use such a relationship as is shown in Figure 9 by plotting the adjustment for 6 possible buildings, constructed from 3 different heat loss and 2 thermal constants, gives the requisite boiler power that would be recommended. Buildings with low thermal mass, and therefore a low thermal time constant, would be unable to retain the heat stored in the building fabric and therefore would, according to this approximation, require a steep increase in boiler power with respect to the heating schedule inactivity period. When the heating inactivity period is equal to the thermal constant of the building, i.e. the time taken for thermal equilibrium to be reached, then the recommendation is to double the boiler size with respect to the building steady state heat loss. The Plant Size Ratio (PSR) is a succinct term to refer to the ratio of heater thermal power output to the building design steady state heat loss.

$$PSR = \frac{\dot{Q}_H}{\dot{Q}_B} \qquad \text{Equation 5}$$

$$Where\ \dot{Q}_H = heater\ power\ central\ heating\ (W)\ normally\ maximum\ acc.to\ datasheet,$$
$$\dot{Q}_B = building\ steady\ state\ heat\ loss\ (W) typically\ at\ 23K\ temperature\ difference$$

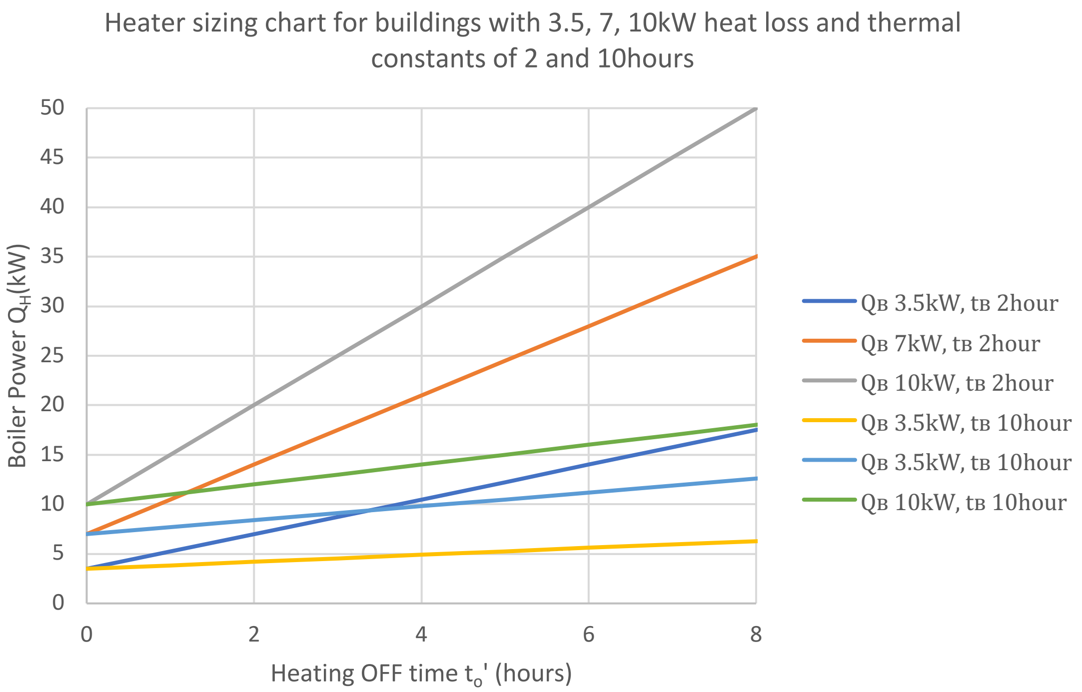


Figure 9: Heater sizing chart for buildings with 3.5, 7, 10kW heat loss Q_B and thermal constants of 2 and 10hours t_B (Buderus-Heiztechnik GmbH, 2002) (Ch.3)

CIBSE offers a simpler set of discrete multiplication factors, based on a separation of buildings into fast or slow thermal response. The factors replicated in Table 1 show that for buildings with blocks of 12 or more hours of heating, no adjustment to the plant size would be necessary regardless of building thermal response. When the heating schedule is shorter then notable increases in plant size would be recommended for fast thermally responding houses, up to a practical maximum of 2.8.

Table 1: Plant size multiplication factors according to building thermal response (Butcher et al., 2015)

Daily hours of heating ON time t_0	Multiplication factor acc. building thermal response	
	Slow f<4	Fast f>4
12	1.0	1.0
6	1.1	2.0
4	1.2	2.8

The factors in Table 1 are derived from Equation 6 and 7.

$$\dot{Q}_h = \dot{Q}_b \frac{24f}{t_0 f + (24 - t_0)}$$ Equation 6 (Butcher et al., 2015)

where f is the thermal response factor, a ratio of cyclic response to thermal transmittance

$$\boldsymbol{f} = \frac{\sum(\boldsymbol{AY}) + \boldsymbol{C_v}}{\sum(\boldsymbol{AU}) + \boldsymbol{C_v}}$$ Equation 7

where $\sum(AY)$ is the sum of the products of surface areas and their corresponding thermal admittances ($W{\cdot}K^{-1}$), $\sum(AU)$ is the sum of the products of surface areas and corresponding thermal transmittance over surfaces through which heat flow occurs and C_v is the ventilation conductance ($W{\cdot}K^{-1}$). As a ratio of cyclic response to thermal transmittance it is possible for a highly insulated but lightweight structure to have a high thermal response factor indicative of a thermally massive building. This is in keeping with the time constant methodology preferred by the Buderus Handbook (Buderus-Heiztechnik GmbH, 2002)whereby it is not the thermal mass of the building itself which is significant but the speed at which it responds to cooling and heating.

CIBSE makes it clear that such formulae are intended as rules of thumb and should be used as a first approximation of the plant size only, with a more detailed assessment by means of a dynamic simulation. The matter is further complicated by the difficulty of assessing the building heat loss, there are many aspects of the building fabric that result in, through variance of materials, construction techniques and other processes, in an as built dwelling whose heat loss differs to the original plan.

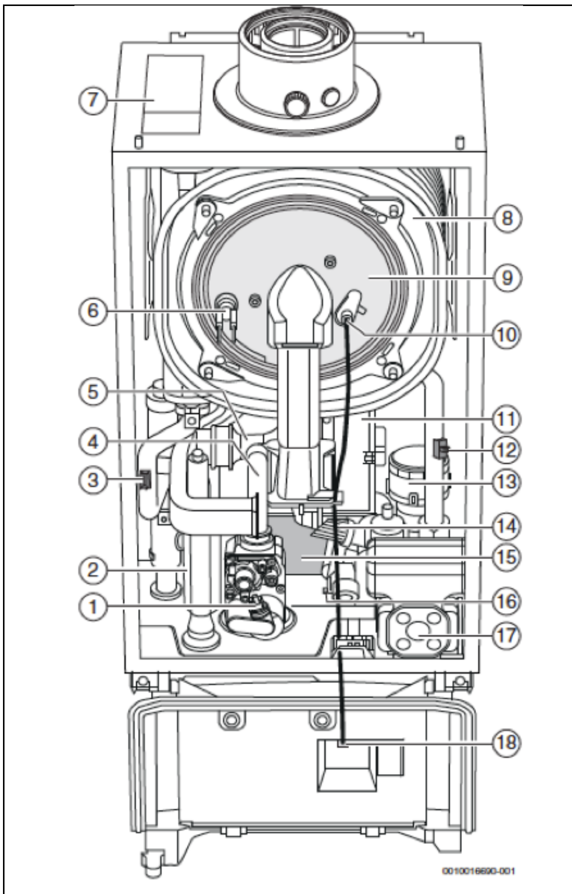
This aspect of the performance gap is widespread and the methods for measuring in situ heat loss are described in more depth in section 2.4. Only through understanding the building fabric and the dynamics can the effects of emitters, distribution system and heat source/storage be accounted for.

Other factors can affect the heating system sizing after selection, radiators, unlike many other components in a central heating system must be located where the heat is required to be delivered. The placement of the radiators in the living space means that purely technical aspects will vie for priority with issues of aesthetics, practicality and disruption. Emitters and piping have few major failure modes, with the exception of leakage through corrosion, meaning operational lifetime can significantly exceed the more complex components in the heating systems such as boiler, pumps and valves (BMJ, 1999). When one considers these issues and the ever-present factor of cost, the longevity of existing distribution and emitter systems within dwellings is likely to be larger than that of the heaters and boilers themselves. Practical and aesthetic considerations of size and location determine the reality of how boilers and radiators are chosen which means that these sizing rules can rarely be followed precisely. Boilers are manufactured in discrete power ranges meaning an exact match for the building loss is unlikely and the heating installer is prone to influence both internal and external (Wade et al., 2016). The role of installers in the design setup and operation of domestic heating systems is one that cannot be underestimated. Their experience, motivations, prejudice and influence affect many aspects of building energy use, from specification of the heating system hardware to heating profiles and user interaction (Wade et al., 2017), for example when they act as on site trainer for the home owner to explain and set up the heating controls.

2.3.3 Gas Boiler

The residential heating sector in the United Kingdom is dominated by one technology, the gas boiler which in 2007 accounted for 86% of the heating systems of England (DCLG, 2007). The layout of the common components of a modern condensing boiler are shown in the figure below:

Figure 10: Condensing combination boiler main components (Nefit, 2017)



1	Gas valve
2	Condensate siphon
3	Flow temperature sensor
4	Gas pipe
5	Venture
6	Burner thermostat
7	Information plate
8	Main heat exchanger
9	Burner
10	Ionization & ignition electrode
11	Fan
12	Return temperature sensor
13	Diverter valve
14	Pressure sensor
15	Plate heat exchanger
16	Flow sensor
17	Pump
18	Ignition cable

The basic operating principle of a gas fired boiler is to use the chemical energy in natural gas released during combustion to heat the working fluid of the heating system. Whereas in the past fireplaces used the chemical energy of coal to heat, most of the heat energy released would be drafted up the chimney through convection. The goal of gas boilers (and by analogy oil, wood pellet and other chemical fuel-based combustion heaters) is to extract as much of the thermal energy as possible from the fuel's calorific value and transfer it to the distribution network while minimising the losses to the flue or chimney. The goal therefore would be 100% conversion of the chemical energy to heat in the heating system, by reducing the temperature and humidity of flue gas to those of the external air. Because the combustion of these hydrocarbons generates predominantly CO_2 and H_2O, the chemical energy contained in a unit has two definitions, Gross Calorific Value (GCV) and Net Calorific Value (NCV) which differ in magnitude by the latent heat of vaporisation of the water produced from the fuel's combustion, for pure methane this would be 39.8 and 36.6MJ/m^3 respectively. The composition of natural gas varies with the proportion of methane, ethane and other constituent gases, the grid delivers gas within a tolerance of 37.5 MJ/m^3 to 43.0 MJ/m^3 which is monitored at reception terminal and various other locations in the network (NationalGrid, 2018), the resulting measurements are used to calculate bills on energy basis and national statistics, e.g. in 2017 the NCV and GCV gas consumed was 35.6 and 39.5MJ/M^3 respectively (BEIS, 2018). Therefore, any meaningful definition of the thermal efficiency of a hydrocarbon combustion-based heating system should use the GCV to exclude efficiencies higher than 100%. The efficiency of this conversion is in practice dominated by the temperature at which the central heating water returns from the heating circuit and enters the primary heat exchanger (given that the temperature of the gas flame is relatively constant and comparatively high). The most significant advance in gas boiler efficiency in recent years hinges on this principle, by exploiting a low enough return temperature to allow condensing of the combustion products in the heat exchanger and thereby unlocking the latent heat within, thereby allowing the conversion to approach the full GCV as opposed to the NCV (Jones, 2014). The relationship between boiler efficiency and the flue gas temperature (closely related to the return temperature and heat exchanger efficiency) is shown in Figure 11 (Ham and Dubbeld, 1985). The flue temperature at which the combustion water begins to condense is 58°C, this would represent the practical maximum efficiency of a 'conventional' (non-condensing) boiler; since the condensate is damaging to the heat exchangers. At flue gas temperatures below this the efficiency increases but not as steeply as that above the condensation temperature.

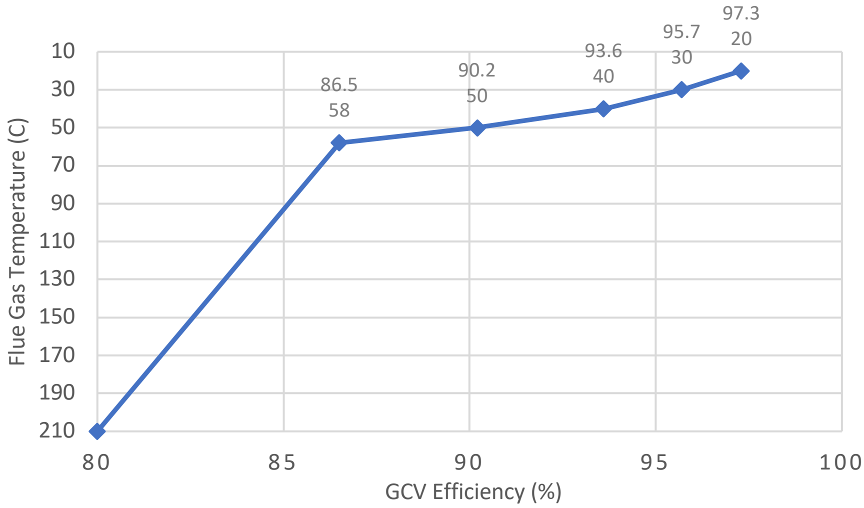


Figure 11: Boiler efficiency as function of flue gas temperature (Ham and Dubbeld, 1985)

Boiler efficiency not only depends on the flue gas temperature, but the ratio of gas to air also plays a critical role in the combustion process affecting efficiency and emissions. The dew point temperature of the combustion products depends on the gas/air ratio, the data presented in Figure 11 is valid for stoichiometric combustion with a chemically ideal gas/air ratio. λ is a convenient parameter for representing the gas/air ratio of combustion relative to stoichiometric, meaning λ of 1 would be stoichiometric, larger than one would be lean and less than one is rich. Moving away from stoichiometric to gas lean combustion reduces the dewpoint temperature, thereby reducing the efficiency potential, moving to gas rich has its own drawbacks by increasing the risk of incomplete combustion and CO emissions, presenting a safety risk.

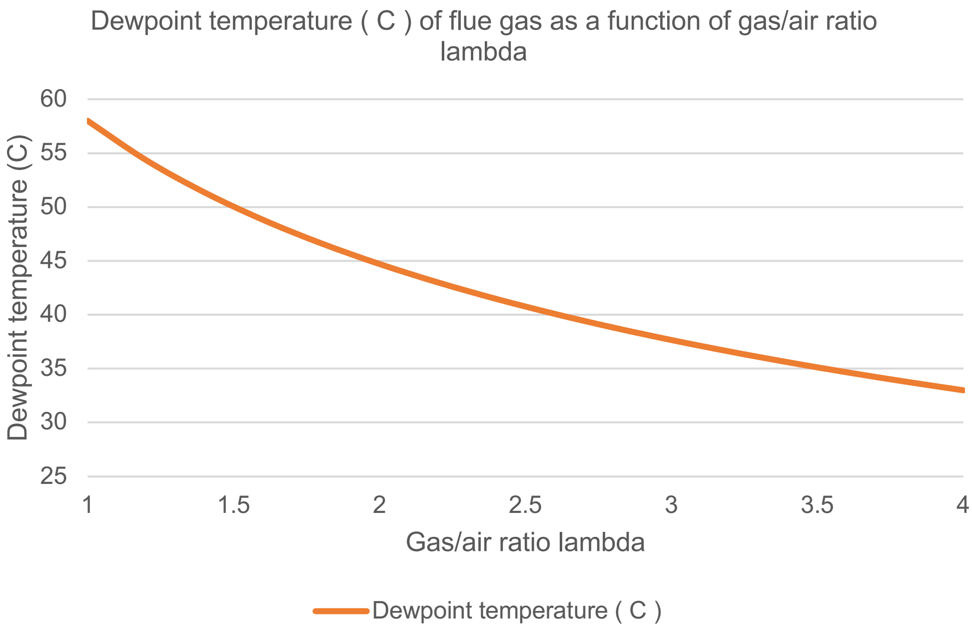


Figure 12: Flue gas dewpoint temperature as a function of lambda (Buderus-Heiztechnik GmbH, 2002)

Condensing the water from the flue gas to release the latent heat is not a benefit which comes without a price, natural gas has additives and impurities as well as nitrous oxides from the combustion, which result in acidic and corrosive condensate in the heat exchanger which needs to be removed. In practice conventional, non-condensing boilers would not operate too close to flue gas temperatures of 58°C due to the risk of localised condensing in the heat exchanger which would lead to corrosion of the materials and reduced lifetime of the boiler (Day et al., 2008). Condensing boilers, however, have heat exchanger designs, both in terms of material and layout, which can cope with the acidic liquid condensate by-product of combustion.

In contrast to internal combustion engines, the efficiency of a gas boiler is not significantly affected by the load at which it is operating, analogous to the engine speed/revolutions per minute (rpm) in automotive language. Conventional, non-condensing boilers were originally designed as fixed output appliances, with fixed flow rate gas valves. Also called atmospheric boilers, the combustion air would be entrained by the gas flow at the burner to allow combustion, the gas/air ratio being determined by the fluid dynamics within the appliance. By the use of a permanently lit pilot flame, or later spark ignition, the mode of operation was via opening and closing the gas valve and thermo-element to check that ignition had taken place and a stable flame had been established. With the addition of variable flow rate exhaust fans and multi flow rate gas valves a degree of modulation was introduced, but it was not until the joint innovations of premixing the gas/air before the burner, and the larger or secondary heat exchanger (designed with corrosive condensate in mind), that boilers could fulfil their efficiency potential. Although this may at first glance seem to indicate that gas boilers are a thermodynamically simple and robust form of heating technology, in terms of the contributing factors to operation and efficiency, the reality is, as always, more complex and the continuing development of boilers reflects this.

2.3.3.1 Combination boilers

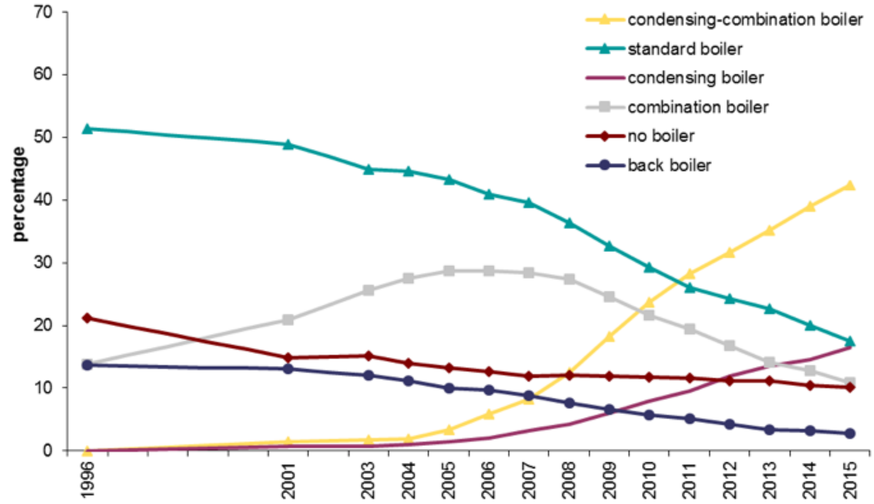


Figure 13: Growth of combi boilers in UK heating market (DCLG, 2017)

Combination boilers have dominated the boiler market in the UK and therefore also the residential heating market in recent years. The growth in popularity of combination boilers has been the case since the 1990s and has continued after the change in legislation mandating condensing boilers (ODPM, 2005). Combination boilers seem to be preferred because of their relative simplicity and compactness, which also contributes to lower overall heating system investment costs. They do, however, present a challenge in design that was touched upon at the start of section 2.3.1, namely that by combining hot water and heating in one appliance a trade-off of primary heat exchanger size must be made. A cursory look at the magnitude of the two heating demands shows that a tendency to size for the larger heating requirement will lead to a potential oversizing with respect to space heating.

Hot water heating capacity requirement is specified based on the maximum instantaneous heat demand, which for a combi appliance is the maximum hot water power demand that can occur in a dwelling. Given that the cold water inlet temperature varies within a known range throughout the year (BRE, 2014), and hot water outlet temperature can be assumed to be constant, then the main contributing variable is the flow rate. As a simple approximation to estimate the hot water demand, boiler manufacturers often resort to recommending combi boiler models based on the number of bathrooms in the dwelling (Bosch, 2017c) as a proxy for the maximum simultaneous hot water demand. Whether a robust correlation between building heat loss and hot water consumption exists seems unlikely and would not take into consideration fabric heat loss variability. Current surveys show that median building heat loss and hot water demand are already different enough to cause problems for balancing the two heat productions in a combi device where DHW is around 1/10th of the energy demand of space heating (DCLG, 2007, DECC, 2014)

Fixed rate or fixed power boilers were not suitable for combination operation since they would be unable to vary the heat input to maintain a stable DHW temperature across multiple, variable flowrates. However, how a fixed rate boiler behaves in space heating operation and the relative magnitudes of losses is useful in placing modern boiler in context considering flue gas losses. For a building of known annual space heating demand e.g. 10,000kWh, 2 separate boiler installations can be considered, one of 20kW and one of 10kW both with a theoretical GCV efficiency of 93% (7% loss through flue gas) (Buderus-Heiztechnik GmbH, 2002) Table 2.

Table 2: Fixed rate boiler operation and losses comparison

Boiler	Boiler operation time	Flue losses
20kW	10,000kWh/20kW = 500h	20kW*0.07*500h = 700kWh
10kW	10,000kWh/10kW = 1000h	10kW*0.07*1000h = 700kWh

This simple calculation implies that the size of boiler would make little difference to the efficiency of the system but as a first approximation it makes a number of assumptions, most critical of which is that the heat demand and efficiency would remain the same for the two different heat system options. For fixed rate boilers the efficiency is still dependent on the heating water temperature, which may not be constant, and secondly, the heat demand depends on maintaining the same internal temperature with both heating systems, something that may not be possible if the control system is limited to pulses of heat from the boiler.

By developing boilers with variable rate/modulating power output levels then not only could this be used to facilitate direct hot water heating it could also be used in space heating mode by enabling improved room temperature control but this dual functionality and modulating might have an effect on efficiency. If it was possible to have wide modulation range of heat production in the boiler without affecting efficiency then a mismatch between the two operating modes may not be problematic, however, current pneumatically controlled premix gas valve technology[3] is limited to a modulation ratio of 1:10 in the newer appliances (Bosch, 2017c), with 1:6 being more common. A practical

[3] Current market dominant technology is based on a pneumatically controlled premix method, whereby the inlet air is drawn by a fan into the appliance and the resultant under pressure is used to open and regulate a gas valve allowing the gas air mixture to be regulated in the desired ratio for efficient combustion.

result of this limited modulation range is that a boiler with maximum output of 36kW can normally modulate to a minimum of 6kW. If such a boiler were placed in a $100m^2$ dwelling with 2 bathrooms but a design day heat loss of approx. 6kW then one can see that cycling behaviour in heating operation would be inevitable in the colder winter months, although the 36kW would equate to a not unreasonable maximum 13 litres/min of DHW (at a temperature increase of 40K) of DHW for which the boiler would be reasonably sized. Since the design day heat load is chosen to account for the coldest expected days, milder winters will result in a lower building heat load and larger mismatch, furthermore outside the coldest winter months and in transition periods the situation will only worsen. Although it was stated that the efficiency of gas boilers is robust regarding part load operation it is not independent thereof, with testing for product energy labelling reflecting that fact, with measurements at full and 30% load (GSE, 2012b). Furthermore, the effect of cycling on the return temperature, is known to be a major influencer of efficiency, but is less well understood in practice.

Trials, such as the BRE condensing boiler assessment (Hayton, 2009), can shed light on empirical relationships which impact efficiency in practice and help to construct assumptions that find their way into the calculation methods leading to the EPCs described in the previous section. Both this study and a similar study in Germany (Wolff et al., 2004) show that the quoted efficiency measurements of condensing gas boilers, according to EU standard measurement methods (De Paepe et al., 2013) are not met in the real world or sometimes even when repeated in other labs.

The discrepancy between lab measurement and real-world measurement can be considered partly analogous to that from the automotive sector where, especially in the case of diesel where fuel frugality is a selling point, the differences can be shocking to the public and the media (Dalton and Steinhauser, 2015) and lead to reduced trust in energy labelling, manufacturers and maybe even energy efficiency as a whole. Of course, many differences in the technology and application exist which prevent a direct comparison, but a few pertinent points are worth taking note of. The current boiler laboratory testing bears more than a passing resemblance to the testing conducted on automobiles, where standard emission testing developed in the late 90s and 2000s to replicate the complex dynamics of real world driving into a standard test (EEA, 2016), has shown itself to be insufficient for capturing real world driving dynamics, with calls for further improvements following recent diesel scandal events to move to a more ‘realistic’ testing on the road, and an acknowledgement of the wide variation in emissions that can occur under different driving and testing conditions (Giakoumis and Zachiotis, 2018). In contrast, as will be discussed later (sections 2.6.4 and 2.6.5), the testing schedules for heating appliances are even more basic in their assumptions and have shown little evolution in recent years. Since regulation informs and restricts the development of the technology it governs (such as the step change to condensing boilers in the UK in 2005 (Elwell et al., 2015)), unintended poor outcomes can result without legislator or industry necessarily abusing the regulations, but where incremental or misinformed changes lead to eventual dysfunctional regulation that can impact on the product performance.

As a pre-condition for standardising a measurement procedure (discussed in more detail in section 2.6.4) , such as that for the efficiency of heating devices, and beginning to understand the dynamics performance of boiler, it is necessary to look first at the boundary conditions which govern the behaviour beyond that of the general thermodynamic principles mentioned already. Whether the thermal output range of a boiler has an effect on the efficiency in practice is covered from a theoretical perspective in the Buderus Handbuch für Heiztechnik (Buderus-Heiztechnik GmbH, 2002), describing that standby losses maybe greater for a larger boiler due to increased surface area of the boiler itself, but standby and running losses depend on radiation to the surroundings and therefore the temperature difference and insulation level of the appliance. Additionally, the heat lost by the boiler to the surroundings through its outer casing can also be considered as waste energy when the appliance is installed outside the living area, such as in a garage or loft as was the case for 27% of boilers in the same trial (Orr et al., 2009). The moderate increase in efficiency at lower modulation levels is often coincident with a lowering of the flow temperature of the Central Heating (CH) water returning to the boiler which, as already explained, is the primary driver of condensing boiler efficiency. Figure 14 shows how this relationship would look for a typical condensing gas boiler, and how a lower operating temperature is advantageous across the modulation range, but whether this is a realistic expectation of a real boiler connected to a real heating system remains to be seen. Mapping the theoretical efficiency at certain combinations of modulation level and flow/return temperature presents a misleading view of real boiler operation. In operation a heating system does not directly control all parameters simultaneously. The boiler may control itself by power modulation in order to maintain a certain flow temperature, leaving the return temperature to fluctuate. Since a flow temperature sensor is essential for safe operation of the boiler and a return sensor is often omitted then this type of control can be found in boilers in the field (Bosch, 2009, Bosch, 2015a, Bosch, 2015b).

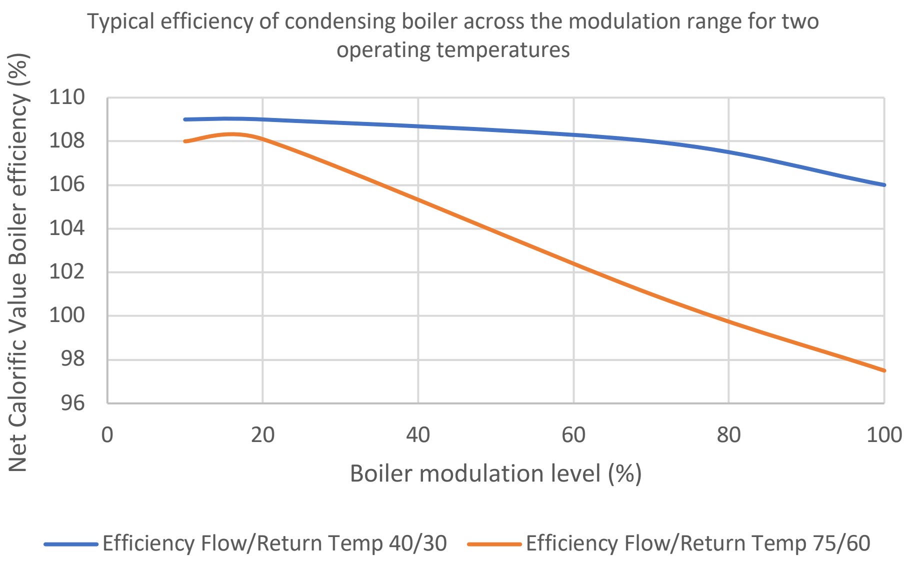


Figure 14: Typical efficiency of a condensing boiler across the modulation range with different operating temperatures (Buderus-Heiztechnik GmbH, 2002)

In practice the boiler is connected to an emitter network and controller which limits ability of the boiler to move deliberately and freely around any parameter space. When a heat demand is generated by the building thermostat or control the boiler should respond by pumping hot water through the heating circuit, in an ideal system the response of the boiler would enable the room temperature setpoint to be reached as quickly as possible without overshoot or delay. An instantaneous achievement of the desired room temperature is not practically possible; many factors can contribute to a delayed and less than ideal control of the room temperature foremost is the unavoidable delay due to the thermal properties of the room itself, which can be exacerbated by lag in the boiler and heating water, control algorithms and placement of sensors.

When the heat demand is below the lowest modulation level of the boiler then intermittent operation is also highly likely and may overshadow the other issues. If the boiler is forced to operate with a series of short (<heating period duration) heating operations interspersed with periods of boiler idle, then this cycling behaviour may not only result in a delayed or irregular achievement of the required room temperature but also other undesired consequences related to efficiency and emissions. Certain aspects of mandatory safety and operational functions of all boilers, coupled with heating system design can lead either to a delay or to the premature termination of the boiler operation before the heating demand has been satisfied. In the case of space heating operation, boilers normally include ‘anti-cycle’ functions which limit the minimum time between burner starts in order to protect the components from premature wear out and the possibility of thermal overload. However, this needs to be balanced against a possible

occupant comfort penalty should the internal temperature drop noticeably, a parameter that depends on more than the boiler internal logic.

The nature of combination boiler functional priority is again pertinent here due to the need to fulfil DHW demands at the expense of an interruption in space heating operation. In the case of DHW mode in combi appliances the burner operation is concurrent with hot water demand so no anti-cycle functions are applicable, but DHW always takes priority on the assumption that an interlude in space heating (determined by the considerable thermal mass of the building) to satisfy a hot water demand will not be noticed, or at least not as much as a failure or delay in providing hot water. Note that any switching of operational mode will necessitate a pause in heating as the burner and pump are stopped to allow the switch over to occur smoothly.

Issues related to heating system design can also affect the operation of the boiler such as include, hydraulic blockage and insufficient heat transfer to the building. These could result in a maximum temperature being reached at the supply temperature (CH water leaving the boiler) sensor in the boiler leading to termination of heat delivery. Hydraulic blockage in the CH circuit could be caused by debris or a mismatch of room controller and Thermostatic Radiator Valve (TRV) setpoint causing the TRVs to be closed and the therefore insufficient heat transfer to the building; with a bypass installed this is analogous to an electrical short circuit. On the other hand, the boiler/room control system also plays a significant role. When the room controller (more detail in section 2.3.7) is only capable of sending a binary heat demand signal, the boiler has no mechanism to modulate down when approaching the setpoint temperature of the room[4], therefore overshoot is to be expected (Bennett et al., 2016). Improvement could be made with proportional controls capable of estimating the required power demand based on the temperature difference, the minimum modulation level of the boiler, typically 20/30% of the maximum output (VROM-Inspectie, 2009), can result in a higher level of energy delivered to the heating system than required and therefore a higher return temperature, eventually resulting in maximum supply temperature being reached.

Regardless of the causes of short run times of the boiler there are a number of effects which can influence the efficiency of the boiler. They include magnitude of standby and running losses, effects of certain safety critical functions, variation of heating water temperature and flue losses. One such function in the case of gas boilers, a pre- and

[4] Analogy with transport is partially valid here, the boiler control is not dissimilar to trying to land a plane without decelerating, or parking a car with only a digital control of the accelerator.

post-purge is necessary to clear the primary heat exchanger of combustion products which can inhibit ignition, the duration of these purge operations is fixed at approx. 30-45 seconds depending on boiler type. The purge operates by using the fan within the appliance, air is blown through the heat exchanger carrying heat out through the flue and out of the property as well as costing electrical energy without contributing to space heating. Simply put, during a heating demand cycle, the shorter the period of operation when the boiler is producing heat (operational time) the more significant the flue loss, due to fixed pre- and post-purge times of the boiler start/stop process, becomes for the overall gross efficiency. The likely variation of flue losses with boiler operation time have been estimated in other research (Orr et al., 2009, Heselton, 1998) and are strongly dependent on the length of cycle. One could compare this to the simple accountancy principle of fixed and variable costs, where, per heating operation, the fixed overheads (pre and post purge, pump overrun etc.) become more onerous as the cycle time and variable costs (gas consumption) decrease, leading to reduced efficiency both environmentally and economically. Combustion based micro Combined Heat and Power also suffers from the same weakness and has been shown in real world analysis (CarbonTrust, 2011) to benefit from heating system integration which favours longer cycle times.

Table 3: Effect of Cycle times on boiler efficiency (Orr, 2009)

Operational time per cycle (seconds)	% loss in gross efficiency
3600	0.0%
180	-1.5%
120	-2.3%
60	-4.1%
30	-6.8%
10	-11.8%

Short operational cycle times, of the order of 3 minutes or less, not only have a negative impact on the efficiency of the appliance leading to unnecessary CO_2 emissions but they also influence the other emissions from the start up sequence itself, other emissions refers to Carbon Monoxide (CO), Nitrogen Monoxide (NO) and Total Hydrocarbon (THC) including Methane (CH_4). These emissions from imperfect combustion form a low fraction of the overall emissions if the boiler is running in a quasi-steady state, but a study of start and stop emissions (Pfeiffer et al., 1999) showed that these emissions increase significantly during boiler start and stop operation. With cycle operational times of the order of 150 seconds THC emissions are 0.8 mgC/kWh for the almost steady state and

95.6 mgC/kWh for the start/stop operation. This means the THC emissions are approx.120 times higher in start/stop operation compared to the steady state.

To try and extrapolate these laboratory measurements to a wider context is not supported by the research so far, and nor has it been attempted, since it was noted in the experiments that the emissions depend greatly on variables such as burner geometry and heating water temperature. The conclusion was limited to the statement that the magnitude of the emission bandwidth is expanded by the increased start/stop behaviour in a distinctly unfavourable direction.

Methane leakage from production and distribution infrastructure has already been identified in the research as an area of concern which can offset the CO_2 benefits of fuel switching from oil and coal to natural gas (Sanchez and Mays, 2015). In the context of domestic boilers increase in emissions can potentially also offset greenhouse gas emission savings when considering that the THC consists mostly of methane, a strong greenhouse gas having a global warming potential (GWP) of $GWPCH_4 = 84$ for $t = 20$ years and $GWPCH_4 = 28$ for $t = 100$ year (Myhre et al., 2013) with respect to CO_2.

With the view that short cycling operation of gas boilers generally negatively impacts expected efficiency and gaseous emissions in a complex way, there is a research gap regarding the prevalence and scale of such issues in the field. In order for condensing combi boilers to build upon their proven track record of energy savings and achieve their full potential in contributing to performance gap reduction, identification of the mechanisms and the causes of short cycles would be necessary, then quantified and considered in standards and legislation. To understand to what extent such conditions occur in real buildings it is necessary to identify and quantify cycling operation of boilers through operational boiler measurements at a suitable temporal granularity. Indirect methods such as temperature measurements on the heating circuit or radiators, have been sufficient for drawing conclusions about daily heat demand (Huebner et al., 2013b) but do not offer the precision required here to cast light on boiler response; heating circuit measure temperatures will lag behind boiler firing and may not respond quickly enough to see short cycles.

2.3.4 Heat Pumps

As part of the wider trend to decarbonise energy in the UK, electric heat pumps are seen as a key component of pathways to a low carbon economy with lower domestic energy demand and achievement of emission reduction goals both in quantitative (Johnston et al., 2005) and qualitative analysis (Lowe, 2007). This transition would involve moving away from combustion based domestic heating systems, such as the boilers previously described. Although heat pumps, as will be elaborated upon in the following section, operate along different thermodynamic principles to conventional boilers, there are commonalities in terms of their interaction with the heat distribution network and cycling behaviour which can negatively influence their efficiency, therefore it is important to recognise in what ways the lessons learnt from today's gas monoculture can be integrated into the technologies and policies of heat pumps.

The generic heat pump (HP) concept relies on the reverse Carnot thermodynamic cycle whereby energy injected into the system as compression work to allow the working fluid to be pumped from the heat source in an evaporated form and condensed at the heat sink to release not only the injected energy but also the latent heat gained during evaporation at the heat source (Figure 15). Therefore, by using a heat source with a stable and renewable temperature and energy level, with a moderate use of external energy the system can achieve an 'efficiency' of more than 100%. For the avoidance of confusion, heat pump effectiveness is calculated in terms of a Coefficient of Performance (COP) for a given set of operating conditions and can exceed one, delivering more heat than the electrical input. The Seasonal Performance Factor (SPF), a measure of HP operating performance over a year, the ratio of the heat delivered to the total electrical energy supplied over the same year, is considered the more useful measure of comparison and ranking of HPs and is the preferred measure for determining government incentives such as the Renewable Heat Incentive (RHI). An SPF of 1 is equivalent to the 100% efficiency limit achievable in conventional combustion boilers but SPFs of 2.5 or higher are common and desirable in the field of heat pumps (Lowe et al., 2017b, Miara et al., 2011).

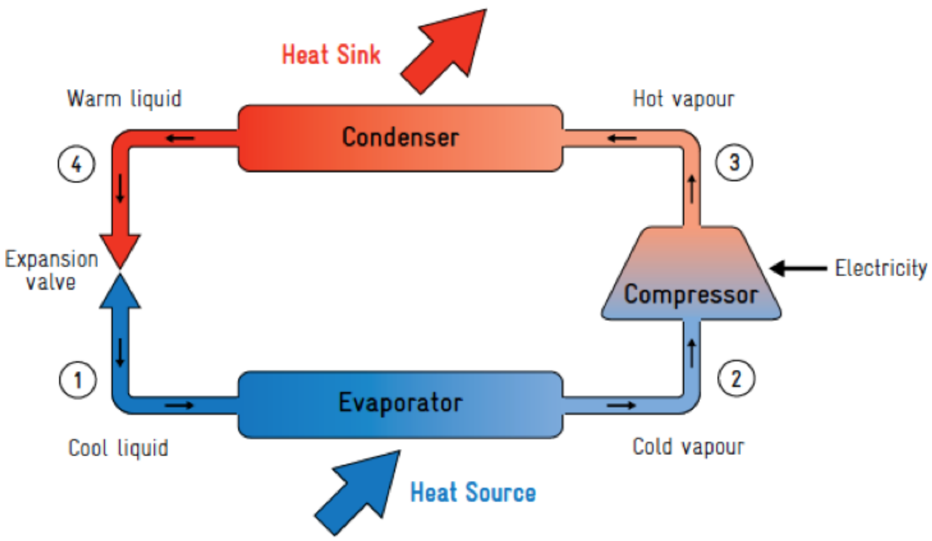


Figure 15: Electric Compression Heat pump principle (EST, 2010)

Renewable technologies such as heat pumps, which are already available in the market have been shown to suffer greatly from issues like design, installation and controls (EST, 2010, Lowe et al., 2017b), highlighting the necessity to understand the parameters influencing efficiency and usability in practice. When these relationships, their magnitude and interaction, are well understood can National Calculation Models (NCMs) correctly represent them and the sector as a whole can progress to fulfil its potential.

It has long been acknowledged that heat pumps will be limited in operation by the basic thermodynamic boundary conditions of operation, namely the heat source and sink temperatures. In practice, this means the minimum temperature of the source from which it 'pumps' the heat, whether that be the outdoor air, ground collector or bore hole, and the flow/return temperatures of the building heating circuit. Heat pumps will be sensitive to the limits and fluctuations of the sink from which they take the heat; choice of air or ground source and the design of the heat exchangers strongly influences the operating potential (Perrin, 2012).

When the heat source temperature limits are reached then heating is maintained normally by means of a simple electrical resistance heater, often referred to as a boost heater. At the point when the booster heater is called upon the system becomes little more than a direct electrical heating device and the efficiency benefits of the HP are lost until the temperatures transition back into the useable range. HPs with real controls are not likely to see such abrupt transitions but are likely to progressively lower the COP as longer or more frequent use of defrost (for Air Source Heat Pumps, ASHP) and/or electrical booster heaters are called upon. This would gradually reduce the COP over the period under observation. Similarly, on the heat sink side, i.e. the internal heating circuit, it is generally advantageous to have lower flow and therefore return temperatures (as is also beneficial for condensing boilers), which require larger heating surfaces such as underfloor heating. Where this is not the case, as is often the case in retrofit situations (McMahon et al., 2017), unless dwelling insulation is also implemented as part of the retrofit, then higher flow temperatures are needed to maintain the comfort despite emitter size restrictions, leading to drops in performance. Heat pumps are commonly limited to central heating circuit flow temperatures in the region of 55°C, meaning direct replacement of a gas boiler, with a maximum of 80°C, is often not possible if comfort requirements and heating schedules are to be maintained. Occupants may also be disappointed to feel cooler radiators and lower radiative heat if they are not aware of the operational differences of HPs and boilers (Lowe et al., 2017a).

From the legislative and consumer point of view, this more complex interaction of influencing parameters on efficiency, when compared to gas boilers, has led to a more complex method of communication with regards to the overall efficiency of the heat pumps on the market. To account for variation in outdoor temperature, and therefore heat source temperature, over the year then Seasonal Performance Factors are defined (thermal energy output/electrical energy input per annum), which should give an indication of the expected efficiency over one complete year, as well as defining multiple COP depending on the expected flow temperatures (Figure 16).

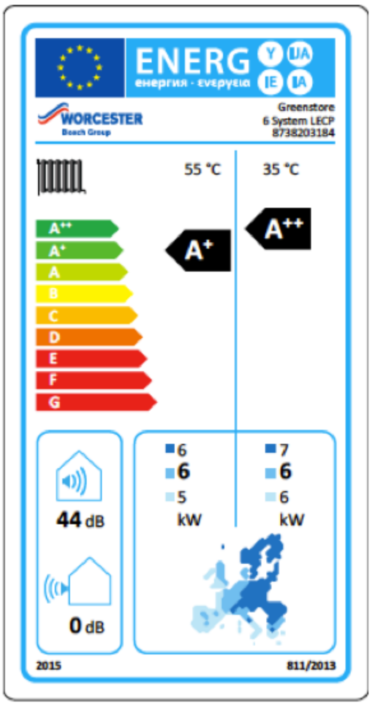


Figure 16: Ground source heat pump energy label for a Worcester Bosch product

Maximum thermal output of heat pumps is generally less than gas boilers when considering product ranges. For example, the leading UK manufacturer, Worcester Bosch produces gas fired boilers between 12 and 42kW (Bosch, 2018b) but Ground Source Heat Pumps (GSHP) between 6 and 11kW (Bosch, 2018c). The difference in output is exacerbated by the difference in price, or cost per kW of heat, which puts pressure on homeowners and specifiers not to oversize systems, pushing a tendency to plant size ratios of closer to 1. Additionally, HP heating power outputs are dependent on the environmental conditions and may in practice be less than these headline figures (Lowe et al., 2017b). The combination of lower thermal output and lower flow temperatures means that the ability of the HP system to rapidly heat a home, as is currently the norm in the UK if heating patterns and comfort expectations endure as they are, is hindered to such an extent that a shift in operation mode, from intermittent to continuous is advantageous and expected. The picture is far from clear whether shifting from intermittent to continuous is environmentally and/or financially advantageous and is determined by a complex technical interaction of heating circuit temperature, SPF and heat emitters, made more complex by homeowners' perception and expectation (Lowe et al., 2017a). However, it should be possible to offset the increase in annual heat demand incurred by a more continuous heat schedule with good part load performance of heat pumps, thereby increasing overall comfort and saving money and CO_2 (Perrin, 2012). If the uptake of heat pumps becomes more widespread, then many houses may shift their heating schedule patterns from the traditional bi modal ON/OFF (Huebner et al., 2013a) to fully continuous heating or simpler daytime setpoint and nightime setback schedules in search of energy savings, behaviours already widespread in other countries such as Germany. Interestingly, this need not be a conscious intervention by the homeowner since, as has been seen in previous studies, although users often change the control setting from the factory settings this is within certain time and temperature parameters (Shipworth et al., 2010, Huebner et al., 2013b) which could mean that the more complex controls of HPs could effectively implement the shift in heating schedule automatically, either through a change in default settings, weather compensation or pre-heat optimisation algorithms.

It has been clear from field trials, anecdotes and research that heat pumps have often not lived up to their promise (Boait et al., 2011). Therefore, despite the theoretical benefits of heat pumps in terms of efficiency, much research effort has been expended into understanding the way in which the performance gap manifests itself in heat pumps (McMahon et al., 2017).

Analysis of field data collected through the UK Renewable Heat Premium Payment (RHPP) from over 600 Heat pump installations highlighted clearly that performance can vary wildly and is sensitive to the context of many factors not least installation (Gleeson, 2014). Besides the more well-known restrictions on performance discussed above, deeper investigations into the real-world performance revealed general trends, such as Ground Source Heat Pump (GSHP) performing generally better than ASHP and the benefits of underfloor heating, but the wider picture is more complex and there seem to be many confounding factors involved. The RHPP analysis shows interesting indications of correlations between COP and mean monthly load factor, whereby lower load factors (below 0.1) seem to result in drastically reduced COP. Such a relationship would imply that extra care would need to be taken in the sizing of heat pumps and even consideration given when building fabric improvements are made after a HP installation. Cycling behaviour was also widely seen, for example median on-to-on times of 10 min for ASHP and 18 min for GSHP in the Renewable Heat Incentive based trial (Lowe et al., 2017b) and is known to reduce the COP of HPs both in the field and in the lab (Green, 2012) where critical minimum cycling time of 8mins was identified.

It could be argued that existing gas fired boiler technology is more robust in terms of its ability to deliver a consistent efficiency in a wide range of operational conditions. In comparison HPs offer a tantalisingly higher efficiency but not without the pitfall of a potentially handicapped efficiency which, from the research so far, remains a potential pitfall of HP installation and control in practice. However, there is hope as the market matures and lessons are constantly learned, it is important for this research to focus on the aspects of operation which HPs and gas boilers have in common. Cycling and heating circuit temperatures have already shown themselves to be critical to both technologies. Emphasising and deepening the knowledge in this area may offer the opportunity to improve current technologies' performance and avoid pitfalls in the transition to the next generation.

2.3.5 Hybrid & future systems

Further new and renewable technology types are emerging in the market such as the family of micro Combined Heat and Power (mCHP) technologies and hybrid systems, combining multiple heat sources. These residential scale CHP systems aim to improve overall end energy consumption for heat and power by shifting electricity production 'on site' thereby saving transmission losses and enabling utilisation of waste heat, addressing a criticism of the centralised power generation/heat pump scenario. Initial field trials of mCHP found that they are also sensitive to the design and installation in the building, in this case not only with regards to the heating requirement but also electrical consumption (CarbonTrust, 2011), (ENEField (Riddoch, 2012, Bosch, 2013)) in particular the ratio of electrical consumption to heat demand, which can be problematic in the summer months. The situation is further complicated with the introduction of so-called Distributed Energy Resources (DER) such as micro CHP where the energy pricing and Feed in Tariffs feed back to the usage profile of the heating system and energy consumption (Houwing et al., 2008).

The possibilities to supplement a heating system with more than one heat source have long been exploited, such as with back boilers and stoves. This method of 'hybridising' the central heating system has continued with the use of renewable and low carbon sources such as photovoltaics, solar thermal, heat recovery, thermal and electrical storage, heat pumps and fuel cells, or in some cases all such systems together (Voss et al., 1996). Hybrid systems can be thought of as the combination of technologies in such a manner to compensate or compliment the strengths or weaknesses of the other. In many cases this means the renewable technology has an insufficient thermal output to cover the required demand or pays a significant efficiency penalty to cover a wide modulation range, and therefore works in tandem with a conventional boiler type heater which can more easily be controlled to meet peak demands with relatively constant efficiency. The residential heating systems of the future reflect, to a certain extent, the macro challenges of energy networks where a controllable fossil fuelled monoculture of power and heat production is struggling to come to terms with the limitations of renewable and higher efficiency technologies.

2.3.6 Heat networks

Heat need not be generated on site for residential use; heat networks exist, where heat is distributed from a central installation either as a by-product of another process or a larger boiler like system. In the latter case the issues afflicting gas boilers and heat pumps can also be relevant as these can be used as prime movers and the heating water return temperature coming from the network will have a significant effect on the efficiency of the central heating plant and the connected distribution system (Orchard, 2014). These issues can also be exacerbated by the lack of feedback control from the demand side to the central heat generation station, an issue which is in focus in innovation projects within the EU looking at so called smart thermal grids (THERMOSS (THERMOSS, 2017)), analogous to smart electrical grids consisting of distributed generation and advanced control systems and algorithms with the aim of optimising the overall efficiency of the system. Methods can be implemented such as distributing excess heat supply to neighbouring buildings when buffer tanks are full or local demand is low, such as with thermal solar, or maintaining optimal efficiency of thermal production in one dwelling by passing thermal oversupply to the network. Such control methods can not only maintain a higher overall efficiency by avoiding wasting excess heat but also reduce excess thermal supply capacity and therefore reduce overall capital invest and maintenance costs. However, whether such thermal smart grids are practical, implementable and desirable remains to be seen and demonstration is still in the early phase.

2.3.7 Controls

The previous sections describe the main heating system types in terms of hydraulic network and heat source, but these are only brought to life and capable of distribution of heat when coupled with a control system. When one considers the function of a heating system control, to essentially switch on the heating system when heat is needed (heat demand start) and off when the need has been satisfied (heat demand end) then historical heating systems would be easy enough to describe. A coal powered fireplace must be lit when the room temperature is too low, coal added to the fire to maintain the equilibrium, and the fire left to burn out when the heat is no longer required. In this case the occupier acts as both sensor, regulator and actuator in the control system.

With this description in mind it is simple to define precisely where the control system boundaries lie. But with the introduction of a heat source with its own control mechanism responsible for safe and optimum operation then this line can become more blurred. From the days of coal and steam one can imagine the bridge officers of a steamship sending the message to the engine room for a certain forward speed, at which point the engine room workers convert that order into a more complex set of coal feed rates, steam pressures etc, all of which is invisible to the bridge bound ‘controlling’ officers[5]. Although a household may also have a simple ‘controlling’ thermostat (ship bridge) on the wall of the main living area which switches an electrical relay when the temperature strays above or below the desired setpoint, the heating device (engine room) itself has control systems and limits which may operate concurrently with the thermostat and sometimes in contradiction thereof. The modern boiler (section 2.3.3) has algorithms which manages the interplay for the various components within it, ensuring safe operation and avoidance of undesirable conditions which may damage the boiler or the system. Anti-cycle is just such a function which dictates the minimum time the boiler must wait before firing again after a CH demand, this can of course lead to the delay of acting on the building control call for heat. If one takes a more completist view of the control system, as would be advised in a socio-technical approach, then one must also include the occupants of the dwelling as part of the feedback loop.

A control system could be as simple as an ON/OFF switch, increasing in complexity, across timed switching, modulating systems, zonal systems and so called ‘smart’ controls. The framework of the EU ErP directive provides a convenient category system which is also utilised within SAP (Table 4).

---

[5] Such tension between bridge control and engine room actuation has been used to much dramatic effect throughout the Star Trek franchise

Table 4: Heating controls classification according to ErP directive

Class No.	Type	Description
Class I	On/off Room Thermostat	A room thermostat that controls the on/off operation of a heater. Performance parameters, including switching differential and room temperature control accuracy are determined by the thermostat's mechanical construction.
Class II	Weather compensator control	For use with modulating heaters: A heater flow temperature control that varies the setpoint of the flow temperature of water leaving the heater dependent upon prevailing outside temperature and selected weather compensation curve. Control is achieved by modulating the output of the heater.
Class III	Weather compensator control	For use with on/off output heaters: A heater flow temperature control that varies the setpoint of the flow temperature of water leaving the heater dependent upon prevailing outside temperature and selected weather compensation curve. Heater flow temperature is varied by controlling the on/off operation of the heater.
Class IV	TPI room thermostat	For use with on/off output heaters: An electronic room thermostat that controls both thermostat cycle rate and in-cycle on/off ratio of the heater proportional to room temperature. TPI control strategy reduces mean water temperature, improves room temperature control accuracy and enhances system efficiency.
Class V	Modulating room thermostat	For use with modulating heaters: An electronic room thermostat that varies the flow temperature of the water leaving the heater dependent upon measured room temperature deviation from room thermostat setpoint. Control is achieved by modulating the output of the heater.
Class VI	Weather compensator and room sensor	For use with modulating heaters: A heater flow temperature control that varies the flow temperature of water leaving the heater dependent upon prevailing outside temperature and selected weather compensation curve. A room temperature sensor monitors room temperature and adjusts the compensation curve parallel displacement to improve room comfort. Control is achieved by modulating the output of the heater.
Class VII	Weather compensator and room sensor	For use with on/off output heaters: A heater flow temperature control that varies the flow temperature of water leaving the heater dependent upon prevailing outside temperature and selected weather compensation curve. A room temperature sensor monitors room temperature and adjusts the compensation curve parallel displacement to improve room comfort. Heater flow temperature is varied by controlling the on/off operation of the heater.
Class VIII	Multi-sensor room temperature control	For use with modulating heaters: An electronic control, equipped with 3 or more room sensors that varies the flow temperature of the water leaving the heater dependent upon the aggregated measured room temperature deviation from room sensor setpoints. Control is achieved by modulating the output of the heater.

Moving up in terms of sophistication of controls, many rely on weather compensation, a principle illustrated in Figure 17. By actively adjusting the flow temperature of the water coming from the boiler or heater according to the outside temperature then compensation for the heat loss of the building can be made by the change in emitted heat from radiators in proportion to the temperature. The steepness and intersection of the slope with the axis would be settable by the installer or user and represents an approximation of the building heat loss coefficient.

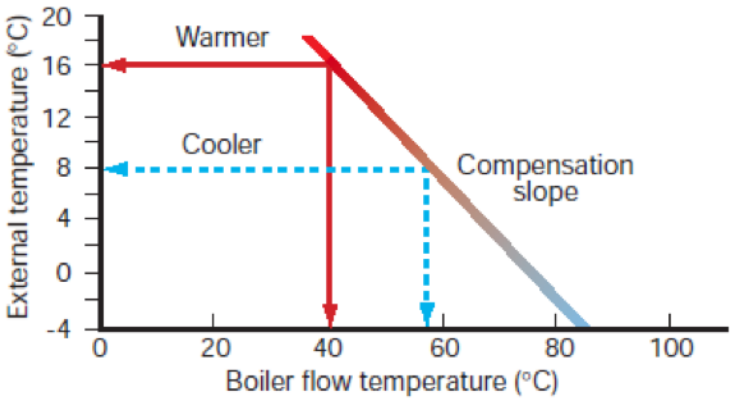


Figure 17: Principle of weather compensation (EST, 2001)

What type and complexity of signal is communicated to the heater will rely on a compatibility of controls, which may not be the case due to competing industrial standards (OpenTherm, 2017) and therefore when combining control and heating device from different manufacturers the simplest common mode of communication is often unavoidable. To take an example from the UK market, thermostat and gas boiler, the room thermostat will send a signal to the boiler to heat when the temperature in that room drops below the required setpoint, in this simple form, such a Class I thermostat will have no hysteresis, meaning that the demand signal will switch from 1 to 0 (no more heat requested) the moment the threshold has been exceeded, depending on the accuracy and delay in measurement. This is not a desirable situation in any control system if it results in a direct translation to the heating device also switching on and off with the same regularity; the consequences can be reduced lifetime of the componentry, poor control or even thermal overload of the boiler. Therefore, internal to the boiler control, control measures are implemented to prevent such fast cycling which can result from small or no hysteresis in the room sensor. These algorithms (anti-cycle) can effectively override the incoming demand signal and block the boiler from delivering heat until a certain time period has elapsed, e.g. 10 minutes.

Human Machine Interface (HMI) between controls and occupants has been identified as a key issue in the socio-technical assessment of heating demand (Shipworth et al., 2010). Lack of transfer of information from installer to occupant (Wade et al., 2017) and confusing interfaces (Combe et al., 2011) leads to a breakdown of the true complete control loop (occupant to heater) with detrimental effects on energy demand. Optimisers, software designed to switch on the heating such as to achieve the room temperature when prescribed by the timer schedule, attempt to compensate for the practice of users programming the heating system in such a way as to buffer the heating and ensure the desired comfort when required, pre-empting the heat up time of the building as illustrated in Figure 18. Smart or learning controls (Yang and Newman, 2013) seek to further unburden the user from programming the controller by 'learning', through an array of sensors, whether heat is required through presence patterns of the residents.

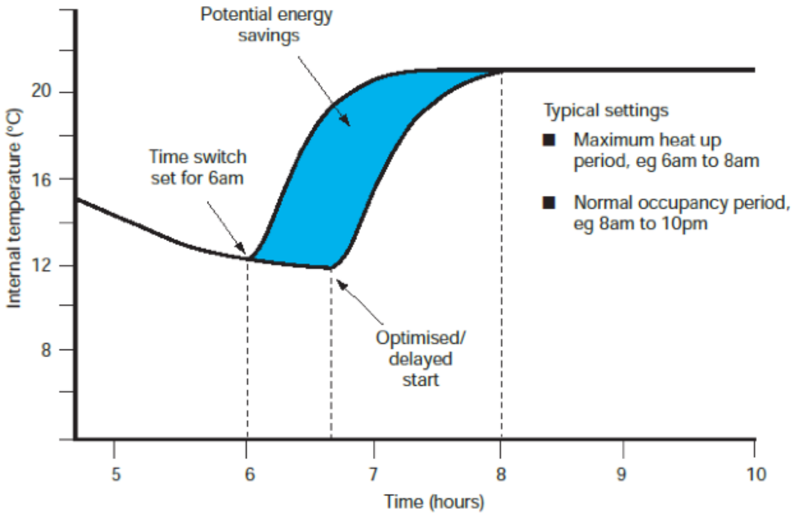


Figure 18: Optimal start algorithm (EST, 2001)

In the case of room controllers, a wide range of controllers are available on the market which vary from simple timers with no thermal measurement of room temperature, to weather compensating and so called 'smart' controllers. How these controls decide when and how to send a demand signal to the boiler is not always transparent. In the case of thermostatic relay control a switch is closed when the temperature rises above a certain threshold (room temperature setpoint, with consideration of hysteresis) sending a demand to the boiler, conversely opening the switch when the temperature is reached and then the demand has been satisfied (again with consideration of the hysteresis). The magnitude of the temperature rise required is not communicated to the boiler and its viewpoint an on/off thermostat, as described, is indistinguishable from a simple timer in terms of the boiler the signal the boiler receives (the closing of a relay) and the way it reacts (by providing a pre-set supply water temperature). Additionally, multiple control systems may be present in the dwelling, such as a room thermostat, linked to the boiler directly, and thermostatic radiator valves which limit the flow rate based on the setpoint at the radiator. If these two systems are not aligned then demand can be requested by the controller but unable to be delivered because of the closed radiator valves. To a lesser degree the same phenomena could be experienced through the under-sizing of radiators, either pushing a condensing boiler into a non-condensing regime, or forcing the boiler to cycle. A number of installation specific features can lead to a disparity between the heat demand and the number of starts the heater makes to fulfil the demand. No one component of the heating system will determine the magnitude of the mismatch.

Conflicting control signals within a heating system, although internally logical can seem confusing when combined in practical heating systems such as the simple thermostat/boiler example above; when the complexity of heating systems increases for example to hybrid systems with multiple heat sources, the outwardly confusing behaviour of the heating system can be baffling to users and prompts compensatory behaviour. The severity, frequency and possible impact of such conflicting effects warrant further investigation both theoretically and in the field.

Reports show that the installed controls in UK homes with boilers were not meeting the required standards set by legislation, 71% of the existing UK housing stock do not reach the minimum levels of controls specified in the current Building Regulations: 38% do not have room thermostats, 45% have no TRVs and more dramatically, 4% of houses with a boiler have no controls at all (HHWT, 2010a); the situation was better when a condensing boiler was installed although still 53% were missing one type of control and 2% had no control.

2.4 Building fabric and heat loss

Heat loss from the building fabric has been of keen interest to legislators and researchers, the contribution of poorly performing building fabric has been identified again and again in practical measurements, often from co-heating tests of new buildings (Johnston et al., 2015). Deeper analysis into the fabric performance gap has identified specific physical and socio-technical mechanisms which can be acted upon, such as the hidden physics of the party wall cavity heat loss (Lowe et al., 2007) and socio-technical aspects of conservatory use (Oreszczyn, 1993). This thesis does not seek to research further the mechanisms and effects of building fabric or its retrofit. The trends are important to be acknowledged in so far as the legislative steps which are moving the building regulations and incentive structures in such a way as to have a meaningful impact on reducing building heat loss in the UK. The trend for lower heat loss per unit area of dwelling (BEIS, 2017b) is the takeaway feature, and how this will drive a further disparity between the DHW and heating peak demand of dwellings.

2.4.1 Building heat loss measurement: Co-heating and other methods

Like the appliance testing previously described, methods have been developed to assess and compare building fabric performance, in particular the heat loss. Assessments can be made on a bottom up basis, taking into consideration the individual components of a building (Henderson and Hart, 2012) which can be useful for assessment of different design options before approving and committing to a build as well as compliance requirements. Post build assessment is done via observation and measurement and must balance accuracy, reproducibility and efficiency (time and cost to test) demanded by the stakeholders of the outcomes, i.e. research, compliance, continuous improvement, market comparisons and EPCs. Possibly partially due to the varied requirements of stakeholders looking to use the results of 'as built' heat loss measurements, no standardised test exists in the same way as British and European norms exist for heating appliance compliance testing. But widely accepted methods have been developed over the years and continue to be improved and reassessed.

The commonly used electric co-heating test method that is predominantly used in the UK, traces its origin back to the late 1970s and early 1980s with the early work of Sonderreger (Sonderegger et al., 1980) and Siviour (Siviour, 1981) and eventually incorporated into the Leeds Metropolitan University Protocol (Wingfield et al., 2010). The principle of a co-heating test is simple enough, but execution and interpretation somewhat more complex and nuanced. By using electric heaters, in an unoccupied house, to maintain the internal temperature at a stable, homogenous level (normally 25°C) for an extended period of time (14-21 days) then the steady state heat loss can be calculated by linear regression of the heat input and temperature difference, internal to external. Uncertainty of thermal mass and steady internal temperature are mitigated with the relatively long measurement period, but additional heat input from solar radiation or heat loss from wind can impact on the reliability of the heat loss calculation. For this reason, the method is a continued area of interest for researchers (Stamp et al., 2013, Stamp, 2015).

Alternative methods have been developed which also aim to provide a data driven, in situ assessment of the building heat loss. An early example was the PRInceton Scorekeeping Method (PRISM) (Fels, 1986), which utilised monthly energy bills and heating degree day data. Energy bills were used as an indicator of the power delivered to the dwelling and therefore the heat input, albeit on a monthly basis at that time. Utilising the simple thermal model below, an estimation for the thermal heat loss could be calculated. (Q_{total}, Total mean daily power demand (W), Q_{base}, Base heat load (W), β, effective heat loss of building (W/K), T_h, balance temperature where building transitions from passive to active heating, T_{ext}, external temperature):

$$Q_{total} = Q_{base} + \beta(T_h - T_{ext})$$

Equation 8: Basic PTG energy balance

Since the total heat input includes the heat from gas (heating, hot water and cooking) with a certain efficiency (η) and electricity (including lighting, appliances) demand as well as useful heat gains from solar and people. The equation can be rearranged and expanded as follows:

Equation 9: Expanded PTG energy balance

$$Gas_{heating} = \frac{\beta(T_h - T_{ext}) - (Gas_{hotwater} * \eta * UF) - Q_{people} - Q_{solar} - Q_{lights,appliances}}{\eta}$$

In this form the energy balance of a building has been used to derive the building heat loss β from gas and electric readings. As in co-heating tests, by taking multiple measurements then it is assumed that solar gain is characterizable by the average over the period of measurement, however, unlike a co-heating test if the data is collected from an occupied house then heat from lights, appliances and people are also included, but the repeated use of the method shows its value in building fabric assessment, by using smart meter data (gas and electric) for building heat loss assessment (Summerfield et al., 2015, Chambers, 2017). Since gas consumption often dominated the energy balance then it may be possible to make a useful assessment with gas consumption alone.

Taking the key element of the PRISM method, namely the Power Temperature Gradient (PTG), and applying it to modern datasets of wider scope and higher temporal detail has yielded detailed assessments of energy savings (Summerfield et al., 2015) and offers a new path for widescale assessment of building performance without intrusive testing in the vein of co-heating. With the advent of easier data collection and the rollout of smart meters in the UK, these methods are being further developed to paint an even broader picture of the building heat loss (Chambers, 2017). It should be noted that the PRISM, PTG and other related heat loss methods are aggregated methods, taking building energy meter data as a proxy for heat delivered to the dwelling while it is occupied. From the point of view of occupancy this poses the problem of unknown behaviours such as ventilation, an aspect usually tightly controlled in a co-heating test (Wingfield et al., 2010) but from the point of view of the heating system an aggregated heat loss could be sufficient for basic sizing and optimisation algorithms.

Assessing, accurately and cost effectively, the Heat Loss Coefficient (HLC) of buildings continues to be of interest to the construction industry (Butler and Dengel, 2013) and new techniques are being continually investigated (such as the IEA Annex 71: Building energy performance assessment based on in situ measurements). Disaggregated data from the heating system offers another way to tackle the measurement of building heat loss, as demonstrated by the use of heat meters on the heating network in a dwelling to measure directly only the energy used for space heating (Farmer et al., 2016). By following a similar methodology to the integrated heating test (Farmer et al., 2016), the stored thermal energy in the heating system can be included in measurements. The heating system distribution network, although of a lower mass than the building fabric, could be acting as a significant thermal storage due to its higher operating temperature, potentially 60°C above ambient.

Connected appliances, fitted with IP connectivity as part of the more general Internet of Things (IoT) trend, offers the possibility to utilise not only smart meter data but also data from the heating system and other heat generating appliances directly.

2.5 Building Simulation

Accurate prediction of building thermal performance came into focus in the 1970s and 1980s (Uglow, 1982). This condition led to the first developments of dynamic simulation programs which would attempt to model building thermal performance by predicting time varying parameters such as temperature, heat flux, energy demand, and weather in complex building environments (Balcomb, 1992).

The use of building simulations, by way of thermal and energy prediction, has served several purposes. The design team of new buildings can ensure compliance with building regulations and optimise designs to achieve or avoid thermal conditions such as summer overheating (Beizaee et al., 2013). Retrofit and renovation activities also benefit from building simulation in similar ways to new construction. The building regulations themselves are developed with the aid of simulations, which increasingly should satisfy cost effectiveness criteria before being released. Heating system manufacturers also use simulation to shape their development process and estimate how new heating systems might perform in buildings (Felsmann et al., 2000). The eventual real-world deviation from the predictions of these simulations is part of the perceived performance gap and acknowledging the difficulties in accurately collecting the requisite input parameters is especially challenging.

Regardless of the goal of a building simulation certain aspects inherent to any simulation must be considered. A balance should be found between the accuracy of the required result and the effort, both time and money, required to achieve it. Additionally, the extra effort of including an ever larger number of input parameters in a quest for increased accuracy has also been shown to have risks associated with increased chance of incorrect data entering the simulation environment which, depending on the sensitivity of the calculation method, may have significant impact on the simulation results (Lomas and Eppel, 1992).

A convenient distinction between two major families of simulation methods can be made based on the time step on which the energy balance is calculated. The longer the interval the more simplifications and assumptions need to be made to compensate for the changes in physical parameters that took part within the time step, most tangible of which is the diurnal variation of temperature and solar radiation. With calculation time steps of a day or longer then such effects are assumed representable as constant over that period.

2.5.1 Dynamic Building Simulation

Dynamic simulations are a category of modern simulation methods where the time steps between the simulation calculations (heat transfer, energy balance) are calculated on a time base that should capture the nuances of transitory time based effects (Crawley et al., 2008). The shorter time steps needed to ensure that dynamic subtleties captured in the simulation methods and results should be of the order of minutes rather than months/days as in the classic simulations. The shorter timesteps still come with an assumption however, in the case of dynamic simulations, the assumption is that all parameters can be considered constant, or be linearly approximated, within the timestep used and no further compensatory assumptions are needed. With this increased frequency of simulation time steps, the computing power required to work through every calculation at every time step has significantly increased for a given simulated duration (e.g. one full calendar year) as in the case of thermal performance of buildings.

There are and have been a large number of dynamic simulation programs developed over the years with various attempts to categorically validate them against empirical data (Lomas et al., 1997) and to quantify the sensitivity of the model to variations in input parameters (Lomas and Eppel, 1992). The conclusions often follow the principle that complexity, especially in terms of number of input parameters, will lead to lower accuracy of results under the guise of high precision (Chapman, 1991).

Commonly used dynamic models from research and industry are EnergyPlus (USDoE) and TRNSYS (Klein et al., 2010), both of which can extend their functionality by means of intermediary software to allow co-simulation with other software packages to expand the simulation capabilities of the standard software. This could be the case for a developer of heating systems or controls wishing to prototype heating system components or control strategies. Detailed simulations of heating systems in buildings using such co-simulation software environments have been limited to in-house industrial settings with limited use in academia for researching novel algorithms or more detailed retrofit analysis (Rysanek and Choudhary, 2012). As such, the use of coupled simulations for the deeper understanding of intra heating system type has not yet contributed to the literature.

2.6 Energy labelling and legislation

Legislation in EU countries attempts to drive progress towards climate change targets by tackling many issues including attempting to provide a level playing field in the residential space for quantifying current housing with regards to energy usage through standardised methods for measuring the efficiency of the appliance as a unit, integrated system (EC, 2013a) and as part of the building (EPBD, 2002, EPBD, 2010). The rationale behind the legislation is that by providing this standardised information the goal of informing 'rational' stakeholders will be achieved and thereby suitable and cost-effective solutions can be invested in and implemented. Whether the provision of more detailed information to consumers is an effective way to alter or nudge their behaviour to achieve larger goals is open to discussion (Waechter et al., 2015). There is a trend to expand labelling schemes (Wiel et al., 2006) in many areas and it has established itself as a staple in the legislative toolbox both for ensuring minimum standards and cross product comparison. The mechanism for achieving the results may not be clear but it is well established and continuing effort is needed to ensure a high level of integrity and quality of the labelling and the methods that support them. This network of EU and national legislation provides one lens through which many of the above issues are focussed, affecting the decisions of consumers and manufacturers alike.

2.6.1 EU context at Building level

The European Commission provides the Energy Performance of Buildings Directive (EPBD) as a framework for improvement of building energy performance, based around 4 main pillars which the member states must implement:

1. Establishment of a national calculation methodology: Implementation of a methodology for the calculation of the energy performance of buildings.
2. Minimum energy performance requirements: Regulations that set minimum energy performance requirements for new buildings and for certain buildings when they are refurbished.
3. Energy performance certificate: energy performance certificate made available whenever buildings are constructed, sold or rented out.
4. Inspections of boilers and air-conditioning: there must be regulations to require inspections of boilers and heating/cooling systems (or a justified alternative system).

The simplified calculation methodologies or static models are used to assess retrofit activities and provide the decision maker with information about energy efficiency and predicted energy consumption (EPBD, 2002). EU member states are required to implement building Energy Performance Certificates (EPC) utilising results from the use of National Calculation Methods (NCM).

The NCM should be based on EN13790 (CEN, 2008), a quasi-static method. Several papers have compared this with dynamic modelling of the building fabric (Wauman et al., 2013, Jokisalo and Kurnitski, 2007, Corrado and Fabrizio, 2007, Deurinck et al., 2012), highlighting the problems quasi-static models have accurately handling the utilisation of solar and internal gains, making assumptions about constancy of these variable gains (metabolic, electrical, solar etc) and heating intermittency which lead to both over and under estimations of energy requirement. As highlighted in the previous section regarding dynamic models, it is disingenuous to compare simplified and dynamic models purely on the accuracy of results gained in a research context, dynamic models have many limitations and weaknesses of their own which must be considered alongside computational accuracy.

It is common practice in these studies to focus on the building dynamics and assume idealised/simplified heating systems. Although this reveals useful results it leaves the question of the HVAC dynamics unanswered, a point raised in the literature (Kim et al., 2013, Wauman et al., 2013) the latter states that EN13790 should not be used for office buildings with intermittent heating and cooling, something that is common in some countries for residential heating.

EU directive (EPBD, 2010) and corresponding regulation is binding for all European countries and stipulates the contents and basic methods for Energy Performance Certificates (EPC), however there is considerable scope in the implementation and calculation method allowed. The aim of the directive is to support implementation of energy efficiency measures that are cost optimal, to achieve "*the energy performance that leads to the lowest cost during the estimated economic lifecycle*". This necessitates, in the context of an EU directive, standardisation of conditions in order to allow comparison between buildings, and interventions in buildings, by means of the EPC. Aspects of standardisation include: definitions of reference houses, occupation patterns, calculation method and lifecycle costs.

Concerning the reference houses, differences will occur with regard to building location and climatic condition, construction date and type and general size and shape, making truly representative pan European, or even national standards often challenging. Additionally, NCMs existed in many EU countries prior to the EPBD. Therefore, freedom is allowed by the directive for the implementation at member state level with EN ISO 13790 provided as the European level framework. International comparison is limited to demonstration of compliance required by the EPBD, limited research such as comparison of Germany and Austria (Gratzl-Michlmair et al., 2012) and isolated comparisons of energy efficiency program (Rosenow and Galvin, 2013). The research in this thesis is, at the time of writing, the first foray into a meaningful comparison of German and British NCMs.

2.6.2 UK context and implementation

The UK implementation of the NCM part of EPBD by the Building Research Establishment (BRE) is approximately according EN ISO 13790. The Building Research Establishment Domestic Energy Model (BREDEM) current simplified BREDEM version (BREDEM 9) forms the basis for the Standard Assessment Procedure (SAP) and the Reduced SAP model (RdSAP) (BRE, 2010)

BREDEM is the design model, SAP is the regulatory model based on BREDEM, and therefore with necessary restrictions on the acceptable input data to make SAP a less arduous system that is still fit for purpose at an acceptable economic cost and calculation accuracy. In the words of the UK Department for Communities and Local Government (DCLG) (DCLG, 2014):

> ***“Standard assessment procedure (SAP)*** *is the government approved methodology for the energy assessment of dwellings. The current version of has been adopted by government as part of the national methodology for calculation of the energy performance of buildings. It is used to demonstrate compliance for dwellings with Part L of the current Building Regulations in England and Wales.”*

> ***“Reduced data standard assessment procedure (RdSAP)*** *is the government-approved methodology for the energy assessment of existing dwellings. A full standard assessment procedure assessment requires details about a building that cannot be seen in a survey or will take too long to collect. This alternative RdSAP methodology is an industry agreed standard that infers for those missing details.”*

2.6.2.1 Development of SAP

SAP can be said to have its origins in the simplified building models of the 1970s, specifically the work of Christine Uglow (Uglow, 1980, Uglow, 1981, Uglow, 1982) which aimed to develop manual building energy consumption estimates using reasonable assumptions regarding heating intermittency and thermal mass as well as simplifications like excluding diurnal variations and heating systems time constants. At this early stage, concepts which can be still seen in the current incarnations of SAP were being developed and implemented, issues such as the effective thermal mass, which is represented by the depth of a planar component that is considered to contribute to the thermal mass and response factor can be traced back to these early works and recurring themes can be found in the literature. Efforts to understand dynamic effects and implement satisfactory simplifications into models are consistently present as the compromise between computational effort (both human and computer) and accuracy is continually reassessed.

How heat sources and gains vary with time and how they interact to effect internal temperatures has been in focus from these early days. Daily peaks of solar gain overlap partially with boiler plant operation schedules, to make calculations of energy demand for time steps larger than one hour then approximations must be made for these types of effect as shown in Figure 19.

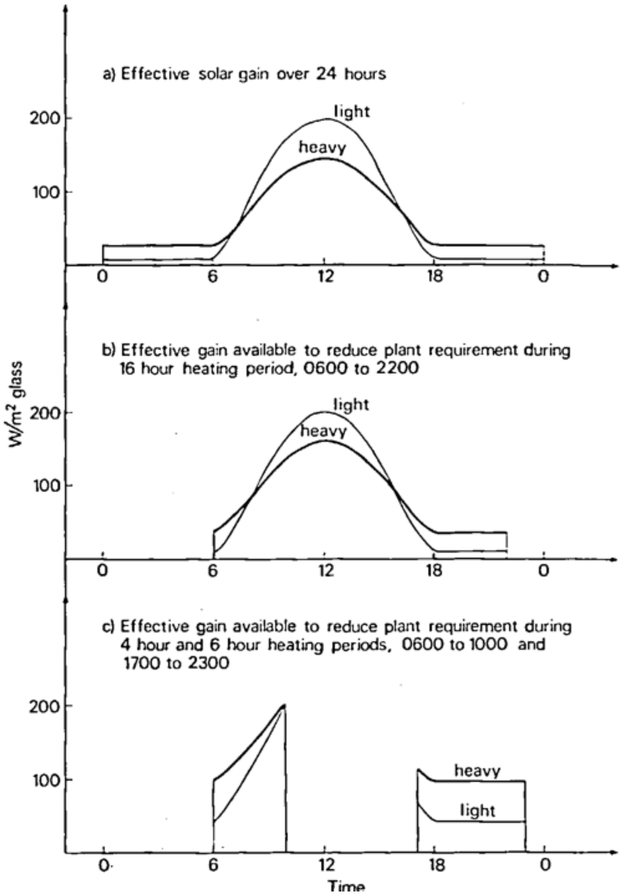


Figure 19: Principle of accounting for solar gain in different thermal mass buildings (Uglow, 1981)

Issues such as variation of plant load during heat up and steady state (see Figure 20) overlap with the tasks of building system engineers during plant sizing (section 2.3.2) but now with a view of how the output changes with building heat load and therefore how the efficiency of the plant may be affected. If the heating schedule and thermal mass of a building is such that the steady state load operation is the dominant condition, then efficiency weightings should reflect that in NCMs, but if the dynamics differ from the idealised situation in Figure 20 then legitimate questions about average plant efficiency could be asked.

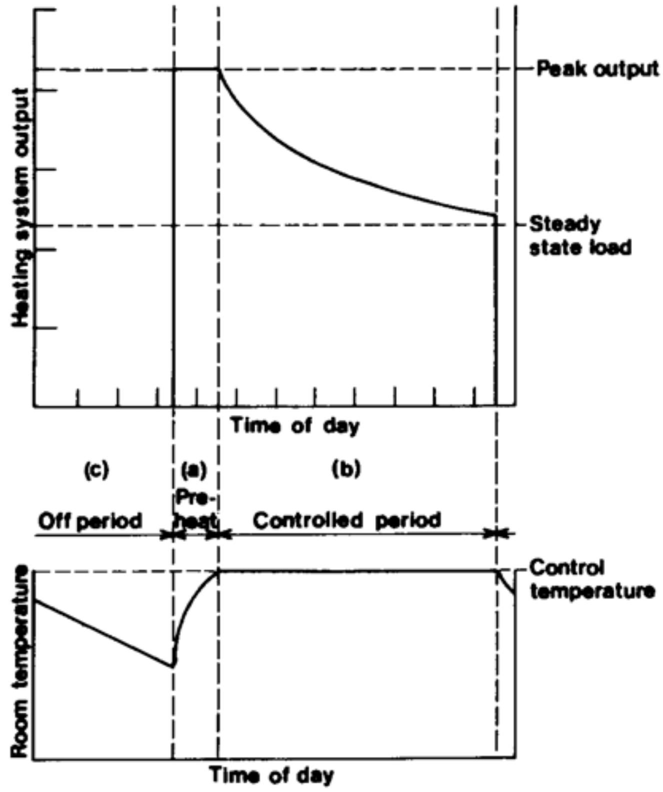


Figure 20: Principle of plant load during warm-up phase (Hitchin, 1979)

The Milton Keynes Energy Cost Index (Chapman, 1990) was developed in the mid 1980s as a way of calculating energy costs and brought together many of the concepts and ideas developed in the preceding decades. In 1991, SAP entered the UK Building regulations and in 2006, with the introduction of new Part L building regulations, became the standard way for all new dwellings to demonstrate UK Building Control compliance with regards to energy efficiency. Recently SAP has been utilised to comply with EPBD for EPCs and as a regulatory tool for financial incentive schemes such as the Energy Performance Contracting and Green Deal.

As a key regulatory tool for energy performance in UK housing, the SAP model has been developed by the Building Research Establishment (BRE, under control of DECC/BEIS) to be easy to use and to enable comparability across buildings and with respect to retrofit pathways. The model selectively parameterises system dynamics using elegant and computationally economical approximations, but with some loss of transparency, and, critically for this thesis, a potential loss of neutrality with respect to heating systems with different characteristics (Kelly et al., 2012). From SAP2009 onwards, the method has estimated the energy required to heat the building month by month, based on steady state heat loss that would occur given the calculated mean internal temperature (MIT), assumed mean external temperature and assumed thermal characteristics of the building (namely U values and thermal mass etc.). Solar, metabolic, hot water and other heat gains are subtracted from the required energy with the remaining heat provided by the heating system. The delivered energy use then depends on the heating system measured or assumed efficiency taken from the approved database (BRE, 2012). SAP assumes that the building is split into two zones, a living zone (Z1), defined as the lounge, living room, or largest public room and the rest of the dwelling (Z2), where the combined floor area of Z1 and Z2 is defined as the total floor area (TFA) of the dwelling. The calculation of the mean internal temperature (MIT) centres on a fixed heating period of:

Weekdays: 9 hours from 0700-0900 and 1600-2300
Weekends: 16 hours from 0700-2300

During these heating-on periods the nominal setpoint temperature is 21°C, which is achieved instantaneously by the heating system at the start of this period and is maintained with no control artefacts such as temperature overshoot. Temperature adjustments are based on the heating control method in Z1, similarly Z2 is adjusted proportionally according to the building heat loss (fabric heat loss, thermal bridging and ventilation loss) per unit of floor area, named in SAP as the heat loss parameter (HLP). Key building parameters of HLP and the thermal mass parameter (TMP) (first implemented in SAP 2009) are defined in the equations (Equation 10, Equation 11) below. HLP is calculated per unit of total floor area (TFA, including voids over stairwells and internal wall thickness) based on the external fabric heat loss (external area, A and respective U values) plus additions for the length and linear thermal transmittance of thermal bridges (L and Ψ) and the air change rate heat loss (derived from air change rate, ACR and building internal volume, V). TMP is calculated from the summation of all building fabric heat capacities using the fabric area A and heat capacity per unit area k.

$$HLP = \frac{\sum(UA) + \sum(L\Psi) + 0.33ACR * V}{TFA}$$ Equation 10

$$TMP = \frac{\sum kA}{TFA}$$ Equation 11

Outside of the heating-on period the mean temperature during the cooldown of the building is calculated based on the building fabric parameters of HLP and TMP. Simplification of the thermal mass assessment is done in RdSAP whereby only layers in the building fabric meeting the following criteria should be summed according to equation

10, starting from the inside surface in the case of external walls or from both sides for internal walls:

- 50% of the thickness
- An insulation layer is reached (defined as thermal conductivity ≤0.08W/mK)
- 100mm depth

TMP has the same units as the material property, volumetric thermal capacity (kJ/m^{3}K), although a distinction should be drawn and the limitations of TMP highlighted. Thermal mass is a term used to describe the ability of a material to absorb, store and release thermal energy and as such is a combination of admittance, emittance and thermal capacity. Thermal capacity is used often, as in SAP, as simple proxy for thermal mass, although it is worth noting that the surface properties (dark, light, reflective etc.) will influence the 'thermal mass' for a given thermal capacity.

A resulting time-temperature profile can be seen in Figure 21 (labelled "SAP Linear"). The notable features of exact room temperature without fluctuation and a linear cooling curve during heating on and off periods respectively, are indicative of the elegant simplicity which permeates the SAP methodology. The resulting 'saw tooth' like temperature profile lends itself to simple arithmetic averaging over the chosen time period, be it day or month. Whether the simplifications pay too high an accuracy price for the ease of computation is a topic this thesis wishes to understand.

Finally, the floor area (Z1 and Z2) and time-weighted combination of internal temperatures during both heating-on and heating-off phases gives the monthly MIT for the heat loss calculation. In this way, the intermittency of the heating system is addressed by modelling continuous heating with a fixed plant efficiency (made up of low and full modulation data) with efficiency penalties/bonuses for control system type.

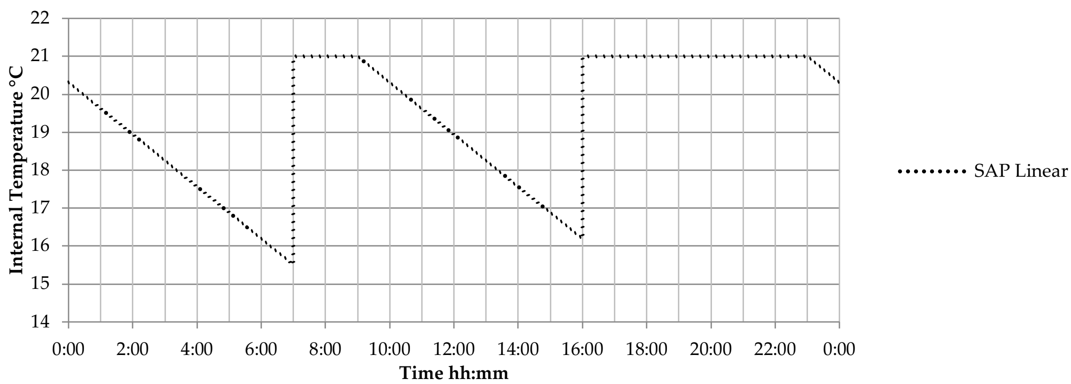


Figure 21: SAP internal temperature profile example from SAP2009

2.6.3 Cultural & regional variation

As outlined in the previous sections, building energy demand depends on a number of overarching factors such as internal temperature, occupant behaviour, building fabric and DHW demand. Although the UK residential case has been explored at length, it helps to inform the research to cast a view beyond these shores. Looking at differences in legislation, especially from the EU, and best practices in building construction and heating system design can provide valuable contrast and a source for improvement ideas. The temperature considered comfortable can vary from country to country or even within a given country over time (Brager and de Dear, 2008). Attitudes to air quality can lead to national conventions of aeration habits even leading to the creation of specific words such as 'Stoßlüften' (ENERGIEFachberate.de, 2016) a type of intense pulse ventilation (with no widely accepted English translation) which is common practice in Germany as a method of air exchange to minimise mould build up and ensure reasonable air quality. It is even required in many standard property rental contracts (DeutscherMieterbund, 2017) & see Appendix 9.1).

Heating patterns and heating seasons can also vary regionally. UK residents favour a bi-modal heating schedule (typified by operation 0700-0900 and 1600-2300 seen in research (Huebner et al., 2013a) and formalised in the Standard Assessment Procedure (DECC, 2009, DECC, 2012)) whereas in Germany the residential central heating system is normally active all day and night with a different setpoint temperature during the day and a so called 'setback' during the night; the scheduling of the heating and the setpoint thereof is also included in rental contracts in Germany (DeutscherMieterbund, 2017). In Appendix 9.1 it is stipulated that in the heating season (defined as between 1st October and 30th April[6]) the landlord will ensure a room temperature of at least 20°C between 0600 and 2300. The described heating season mirrors the common practice of using winter tyres in Germany from 'O to O', or 'Oktober zu Ostern', meaning October to Easter. Whether, or to what extent an intermittent (UK type) heating schedule differs from a variable (German type) in terms of experienced comfort and energy efficiency is a topic that often sparks heated debate between experts and non-experts alike especially in the context of weather compensated controls (BEIS, 2016) and as such always warrants investigation. Crucially this superficial difference in heating strategy may lead to similar energy demand outcomes when looking deeper into the thermal response in the building physics and the intermittency of the heating system.

[6] Heating demand outside this defined heating season is also described in the rental contract, namely if the outdoor temperature is measured below 12C at 1200 on 3 consecutive days, this gives an indication of the expected thermal constant of German buildings and the rate of change of atmospheric temperature.

2.6.4 Nexus of NCM and Product labelling: Boilers in SAP

SAP is a calculation method and as such describes a procedure to be followed in order to estimate the energy consumption of a building, this requires the input of data from the building under consideration. In the case of the building fabric this is a description which is then converted to a thermal parameter via a table of standard values, in essence assuming consistent high build quality and all building materials are of equal quality and thermal efficiency (a challenging process in its own right (Clarke and Yaneske, 2009)), more contributory issues to the performance gap. In the case of heating systems, the procedure is more involved in order to take account of the performance differences between manufacturers and models. SAP references standard values for the efficiencies of the main technology types such as boilers but also offers the option to take the data from the PCDB (Product Characteristics Database, (BRE, 2017)) an extract of which is shown in Figure 22, should the data be available, but also overlays adjustment factors within the SAP calculation itself according to the values in Table 5. The PCDB is in fact a voluntary declaration of performance measurements by the manufacturers of the products, albeit measured in conformance with the relevant standard by a recognised or approved body. Measurement of the efficiency is according to European norm EN15502 (CEN, 2015b) which has been adopted into the British Standards (GSE, 2012b) and is considered a good benchmark in global standards (Bourke et al., 2014) but is still subject to variation in results across the certified bodies responsible for testing (De Paepe et al., 2013). The PCDB is managed by BRE under contract from the Department for Business, Energy & Industrial Strategy, BEIS (formerly managed by the Department of Energy & Climate Change). The PCDB is currently in the process of being aligned with the newer EU wide database of product performance data, Ecodesign (EC, 2013b), which was recently expanded in 2015 to include heating appliances and systems, a step beyond the appliance only approach of PCDB.

Type	Index number	Status
Gas and oil fuel boiler	017511	Normal
Brand	**Model name**	**Model qualifier**
Worcester	Greenstar	28CDi Compact ErP

Boiler ID*	47-406-77
Fuel	mains gas
SAP 2009/2012 annual efficiency (%)	89.8
SAP winter seasonal efficiency (%)	90.7
SAP summer seasonal efficiency (%)	87.0
Comparative hot water efficiency (%)	74.9
SAP 2005 seasonal efficiency (%)	90.5
Efficiency category	SEDBUK based on certified data
SAP equation used	104
Output power (kW)	24.0
Electrical power when firing (W)	97
Electrical power not firing (W)	1

Figure 22: Example gas boiler performance data from PCDB (BRE, 2012)

$$\eta = 0.5(\eta_{full} + \eta_{part}) - 2.1$$

Equation 12 (an efficiency penalty for pilot light operation has been omitted due to its low prevalence in modern boilers)

At this stage, it is worth noting the implicit assumption of SAP regarding boiler efficiency. The simple average, no weighting, of steady state efficiencies in Equation 12 implies that the boiler is either operating continuously during the heating period with smooth modulation or that any dynamic delay of cycling behaviour is insignificant with regards to efficiency. As described in section 2.3.2 efficiency and cycling have been linked and the topic of plant size ratio is far from being clear cut, the case of oversized combi boilers being a strong example of how other pressures exert themselves on heat source sizing and theoretical PSRs, with the knock on effect that expected modulation levels and cycling behaviour will be equally, if not more, complex.

Table 5: SAP 2009/2012 Seasonal efficiency offsets

Fuel and boiler type	Winter offset $\Delta\eta_{winter}$	Summer offset $\Delta\eta_{summer}$
D1.5: Modulating regular	+1.0	-9.7
D1.9: Modulating instantaneous combi	+0.9	-9.2

Type	Index number	Status
Heating controls	200006	Normal
Brand	**Model name**	**Model qualifier**
Worcester	Wave	ErP Class V

Control category	Boiler Weather and/or Enhanced Load Compensation
SAP heating system category (Table 4a)	2
Fuel	mains gas
Efficiency adjustment for boiler (%)	3
Hours heating off	N/A

Figure 23: Controller data from PCDB (BRE, 2012)

A further inherent assumption which can be derived from the method of boiler efficiency calculation embodied in SAP is that boilers are correctly sized for the building, therefore the ratio of low to high modulation will always emulate that in Equation 12, meaning that two boilers of 98% efficiency, one with 8kW output and one with 45kW output would be treated the same in terms of efficiency and energy consumption. This is similar to the so called ‘energy efficiency fallacy’ (Waechter et al., 2015) can occur when products of similar efficiency are compared without consideration of their size and, therefore, consumption. This would of course be pertinent in the case of 2 televisions where the usage duration is similar, a large A rated screen would consume more electricity than a small one. SAP, and product labelling in general, assumes that efficiency is a constant heating appliance property and that consumption is dependent only on building heat loss demand. However, there is the possibility within SAP to overlook that different sized boilers may operate differently in the same house, due to modulation and cycling issues, and therefore any tendency by consumers or heating professionals to oversize or undersized boilers, on the grounds that they have the same efficiency, would not be discouraged by the current labelling framework.

The fact that the boiler efficiency at steady state is dependent on the modulation level is already acknowledged in SAP but if the useable range of the boiler modulation level is effected by the sizing relative to the house then there is an argument that such plant size ratio factors should be included in the calculation, furthermore if efficiency and emissions increase in non-steady state operation and that type of behaviour was demonstrated in residential buildings today then there would be further grounds to re-examine the implementation of boiler efficiency and emissions in SAP.

2.6.5 Energy labelling for heating systems and home appliances

Domestic heat source appliances such as gas boilers and heat pumps are mass produced products sold in a competitive international market. As such the influences and pressures which come to bear on the specification and price of the final product should be understood if one is to understand the process that led to the eventual performance envelope of the installed appliance. Within EPCs and NCM it is always necessary to represent the efficiency of the heat source within the context of the building. Standards for how this efficiency should be measured and made available for input to the NCM are subject to similar complexity and national variations as the EPC standards.

Legislation plays its role, in that heating products can be compared across manufacturers by the energy usage labelling which is standardised and compulsory. Most recently this is governed since September 2015 by the EcoDesign and Energy Using Products (EuP) at European level by the European directives establishing a framework for the setting of Eco-design requirements for Energy-using Products and amending Council Directive 92/42/EEC. An example of the labelling format required under EuP is shown in Figure 24. Clearly this will force manufacturers to meet minimum standards (e.g. 86% in space heating for fuel boilers <70kW)(EC, 2013a) and incentivise them to improve the efficiency to improve sales (Schischke et al., 2007). However, uncertainty about content and time plans of legislation can lead to rushed implementation into appliance specifications.

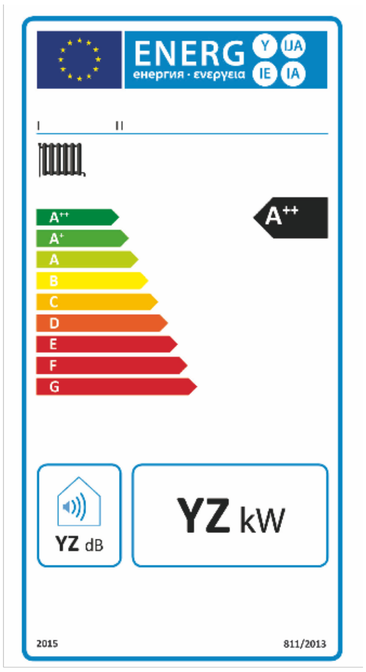


Figure 24: Ecodesign Label template for Space heating appliances (EC, 2013a)

In relationship to SAP, heating product technical specifications are collected in the PCDB (Product Characteristic Database) (BRE, 2012) when the current valid version of SAP includes calculation methods sufficient to use the information directly, this also allows inter product comparison outside of the SAP calculation i.e. for those people contemplating retrofit of heating systems rather than house moving, although it should be noted that retrofit is not always planned, and ‘distress purchases’ are common. The testing of efficiency is simplified for reasons of practicality, repeatability, cost and robustness, for example taking minimum and maximum output measurements at steady state and combining in a weighted average for inclusion in the PCDB. For technologies which are not included in the current valid version then the ‘SAP Appendix Q Database’ is the required reference, for example Heat Pumps were included in Appendix Q when SAP2005 was valid but have since graduated to the PCDB.

In the current dominant case of condensing boilers, trials have shown that the measured efficiencies in real installations consistently deviate from what normative standards estimate (Wolff et al., 2004). Issues include the inevitable variation of heating circuit temperature which is constant in measurement tests such as EN15502, DIN4701 and SEDBUK (all of which rely on steady state measurements and weighted averaging). The magnitude of such effects as this can be changed by factors like plant size ratio and modulation range which effect the utilisation factor and cycling amount (Wolff et al., 2004).

However, manufacturers must consider more factors than legislation or labelling (be it mandatory or voluntary), any stereotypical product development project includes a stage of definition of requirements (Mital et al., 2014). Development of a heating appliance is no different, a heating product specification will contain requirements also in the areas of physical dimensions, installation method, heat output ranges, Human interface features, maintenance features, noise and aesthetic considerations[7]. All of which will have been condensed from previous market experience, customer feedback and market surveys and will serve to determine the feature set and price point in the market in comparison to competitor appliances.

Manufacturers will use a mixture of market research, competitor analysis, legislation analysis, calculation and experience in order to decide which heating technologies will be successful in the marketplace and provide the necessary profit for the continuation of the company. Market forces play a significant part in the pricing of existing technologies (Mital et al., 2014); however, manufacturers can only invest in future technologies

[7] The author’s experience working for Bosch Thermotechnology has included involvement in many projects at the stage of collating, refining and testing of heating appliance requirements.

confidently if the benefit to the customer will repay the investment cost, or if the legislation environment requires a technology either through financial 'carrots' or restrictive 'sticks'. Internally, within the manufacturer, the energy savings and derived financial benefits of various technologies will be compared using dynamic simulation tools and although this may influence the marketing and placement of the product, mandatory labelling will also form part of the public image that will be presented to customers in the market. They could, in such well-established commodity markets where innovation is low and product differentiation difficult, be used to support the marketing. These tools are influencing the market in a way that should be understood so technologies beneficial to the overall targets are invested in.

When one considers that the development time for a new appliance can range between 18 months for a variant of an existing appliance (e.g. UK version of a DE appliance) to 5 or more years for appliances based on new and more complex technology, such as microCHP (CarbonTrust, 2011), with a corresponding increase in development costs, then it is clear that considering the sources of influence on the product specification is important to understanding the final market ready product and its performance. For example the Condensing Boiler, starting with being reported in the literature in 1979 (Bartholomeus, 1987) to commercial release of the Nefit Turbo Boiler 1980 (Nefit, 2015) in the Netherlands, slowly leading to widespread market acceptance which did not come until 1990 (Weber et al., 2002) or in the UK until 2005 through regulation change.

2.6.6 German Building context and implementation

Within the context of a legislatively linked European Union and global production network it is pertinent to look beyond the shores of the United Kingdom to see how related legislation has been implemented against the backdrop of a different sociological, economical, industrial and political environment. When one considers the practice of companies rolling out products in multiple geographic markets with the same challenge of differing or contradictory customer needs or legislative roadblocks then the case for considering other countries becomes more convincing. The case for looking abroad is further underlined by stepping into the mindset of development departments of overseas companies who may design appliances with their own assumptions of market trends in mind which must then be 'translated' into foreign markets (e.g. UK) with mixed results[8].

[8] As an employee of the international heating appliance manufacturer, Bosch Thermotechnology, based in Germany, the author has experience of the international product development process and also the language skills to use Germany as a counterpoint example for this section.

German legal implementation of EPBD is encapsulated in Energieeinsparverordnung legislation (EnEV 2007) and requires the use of calculations according DIN V 18599 (DIN, 2011a), which is applicable to all buildings and has a history predating EPBD. For residential buildings, additional options are available: a simpler calculation method described in DIN V 4701 and DIN V 4108 (DIN, 2012) and a new table-based method for standard configuration of simple residential buildings. As mentioned earlier, the EPBD allows EU member states to implement their own NCM so long as regular reports are compiled to explain deviations. The models themselves (Zerwas, 2008) and EPBD Implementation (Delorme et al., 2012, Schettler-Köhler, 2012) have been well documented and investigated in the literature. Interestingly the German standard allows two methods of calculation of building energy consumption, one based on a standardised reference system and one based on the real historical energy use in the building. The EPC (known in Germany as EnergieAusweis or EnergiePass) does not have to be completed by a qualified professional, home owners or property agents can use independent third-party websites to self-declare the properties of their building and receive a legally valid EPC (demand or consumption) by email (Immoticket24GmbH, 2018). In Germany, the issuing of the certificate is controlled by law and no standardised software is stipulated in the EnEV legislation but regular auditing is required.

Having been implemented differently in Germany compared to the UK, the EPBD covers a great number of topics related to building energy efficiency, and to attempt a comprehensive comparison of the complete EPBD in even just two countries would be a large undertaking. Instead it is more sensible to focus on selected pertinent differences with a view to identifying potential improvements on one or both sides of the comparison. In the case of the German implementation of the EPBD, a striking but simple difference is apparent at first glance at the full DIN V 18599 for building energy demand calculation. The full standard consists of 11 separate subsidiary documents, each concerning itself with a different part of the building energy system:

- Total energy balance
- Room energy balance
- Energy usage of room ventilation system
- Lighting
- Heating
- Dwelling ventilation
- Air conditioning
- Domestic hot water
- CHP, PV and wind
- Boundary conditions

- Building automation

Separating the complete standard into thematically distinct documents is helpful for navigation through such a document, and is essential when one considers the size of the resulting sub documents. Part 5, for example, regarding heating only, weighs in at a total of 163 pages, a considerable increase on the relatively slimline SAP2012 document of 234 pages total which covers all 11 topics of the DIN standard. The relative complexity of the German DIN standard has been noted in a comparison with the Austrian NCM where it was noted that the extra complexity did not seem to result in higher accuracy (Gratzl-Michlmair et al., 2012)

Primarily the difference in length of the two national standards comes from the readiness of the authors to use simplifications in the calculation method. The DIN standard, when viewed superficially, can be considered a somewhat raw interpretation of building physics and building energy balance with little or no attempt to simplify the equations to allow easier implementation. The DIN standard is the base upon which the many independent implementations of the standard can be built, interpretation of the standard is in the hands of the software development team. This contrasts starkly with the more 'pret a porter' philosophy of the SAP standard which can be implemented almost directly in a spreadsheet, simple program or even carried out by hand.

A second difference, relevant to the research to follow, lies within the DIN V 18599 part 10, governing the boundary conditions behind how building energy performance is calculated. Within the boundary conditions described in section 10 is the suggested heating schedule for domestic applications which is 17 hours per day (0600-2300) on both weekdays or weekends. Independent of discussions surrounding implementation of building physics in formal calculation methods, a difference in fundamental boundary conditions such as heating schedule can greatly affect energy consumption predictions even if the calculation methods concur in every other aspect. In the case of SAP, the standardised heating schedule consists of two heating periods per day in weekdays and one block of heating at the weekend. It is of course important that these assumptive boundary conditions reflect the average behavioural trends of the heating usage in the respective countries but they may also be a gateway to understanding the perception of heating not only from the user but also from that of the building and heating industry as well as policy makers and researchers.

2.7 Summary

The performance gap in residential heating demand is a continuing issue in the UK, since gas boilers make up the majority of the residential heating systems and they have been identified as underperforming in the field then they present a valid area of interest. The process of boiler selection, importantly the thermal output, is subject to issues such as finite product specification and in the case of combination boilers, competing priorities due to higher peak demand from DHW than CH. When a possible thermal output mismatch between building and heater is present and the finite modulation capacities of boilers is considered then the known efficiency penalties from inconsistent return temperatures (for condensing) and cycling may prove to be problematic in installations. Bearing in mind that the UK NCM, SAP does not consider variability in boiler efficiency based on its sizing then the potential for misrepresentation of the heating system efficiency is evident.

This thesis seeks to investigate specifically the dynamic effects of heating systems compared to the idealized approximations in SAP in the context of the UK housing stock. SAP (Standard Assessment Procedure) is the designated NCM for UK domestic properties, SAP Version 2009 (BRE, 2010) is based around a monthly heat balance model using average internal and external temperatures. SAP is derived from the established BREDEM model (Building Research Establishment Domestic Energy Model) which has been well documented (Henderson and Hart, 2012). SAP has been compared to a dynamic model (Inverse Dynamics Energy Assessment and Simulation, IDEAS) by Murphy (Murphy, 2012) showing similar predictions of the relative energy demand and internal temperature with both the BREDEM static model and with the dynamic IDEAS model.

Considerable effort has been expended to measure and understand residential heating energy demand, but the specific issue of heater operation within the heating schedule that results therefrom still has uncertainty within it. Conclusions thus far in the literature are based on indirect measurements, either internal temperatures, energy use as measured by the gas meter, or through surveys. Research is missing to support these conclusions via direct measurement from the heating system itself, and a deeper understanding of the mechanisms involved would support continued research into the performance gap, improve information for consumers and support the transition to next generation heating systems. Which raises the possibility to investigate in a novel way compared to previous research but also look at other aspects of the performance gap in a new and potentially improved way. Based on this assessment of the literature, the following two research questions have been formulated:

How are the dynamic behaviours of building heating systems represented in the National Calculation methods for EPCs and does this representation lead to inconsistent calculation of space heating and temperatures?

How can high quality heating system diagnostic data contribute to improvements in building heat demand characterisation?

In many ways, the research that will be presented in this thesis continues and revisits many of the core topics that have challenged researchers in the area of building energy modelling since the 1970s. Namely dynamic versus static, heating intermittency, thermal mass, but most importantly how these concepts interact together and can be represented in simplified, practical and useful models building on previous work (Wauman et al., 2013, Murphy et al., 2011). By revisiting and reopening these topics then it is hoped to bring the field forward by addressing the issues in a modern context, significantly from the point of view of the heating system, which is a component which has a shorter lifetime than the building they inhabit (11.5 years for boilers (DCLG, 2009)) and is therefore likely to be replaced or upgraded many times in the building's life giving multiple chances for the EPC data to be used for decision making.

3 Outputs from this thesis

Two peer reviewed papers have resulted from this thesis by the time of submission

Bennett, George; Elwell, Clifford; Lowe, Robert; Oreszczyn, Tadj. 2016.
"The Importance of Heating System Transient Response in Domestic Energy Labelling."
Buildings 6, no. 3: 29.

Bennett, George; Elwell, Cliff; Oreszczyn, Tadj. 2018
"Space heating operation of combination boilers in the UK: The case for addressing real-world boiler performance"
Building Services Engineering Research and Technology
First Published online August 20, 2018

Further papers are also planned from the work within this thesis.

4 Methods

The strategy to address the aims of this research is to use complementary methods to build a more comprehensive assessment of the dynamic behaviour than would be possible with any one individual method. Using an already validated dynamic simulation environment (Building Technology Simulation Library BTSL) as a tool to contrast the dynamic heating system behaviour against the steady state assumptions of SAP , influencing parameters can be explored in order to assess their impact and the characteristic heating system behaviour that ensues. Beginning by creating a dynamic version of SAP in BTSL which can initially be simulated with an ideal heating system in a test case house, with no inherent physical thermal dynamic properties allowing it to react in the same way as the SAP assumed systems, the baseline for the introduction of a dynamic physically realistic heating system can be built. Then various physically realistic heating systems can be introduced to explore the performance impact of parameters such as plant size and control strategy and how this manifest itself in the boiler dynamic behaviour. With this simulation basis the empirical section of the analysis looks to identify the same symptoms of poor performing boiler heating systems in the wider real-world context and in a more forensic case study analysis. The real-world data will be collected from boiler diagnostic data of a 200+ set of boilers and 4 case studies consisting of boiler data and additional measurements and meta data. With this complementary strategy of analysis, the aim and objectives of identifying and exploring mitigation strategies for boiler poor performance can be achieved. The methods, the data sources and the type of analysis will be expanded upon in the rest of this section.

The outline of the research methods to follow is structured in such a way to build up, stage by stage an investigation into the research questions. In order to facilitate a comprehensive analysis of the dynamic heating system behaviour in question, a mix of methods and data sources are brought together to enable multiple avenues of analysis in search of common themes. The strengths and weaknesses of the respective methods and data sources are acknowledged and, with the aid of the other sources used, partly mitigated. The structure is based on the blocks of work summarised in the following chart:

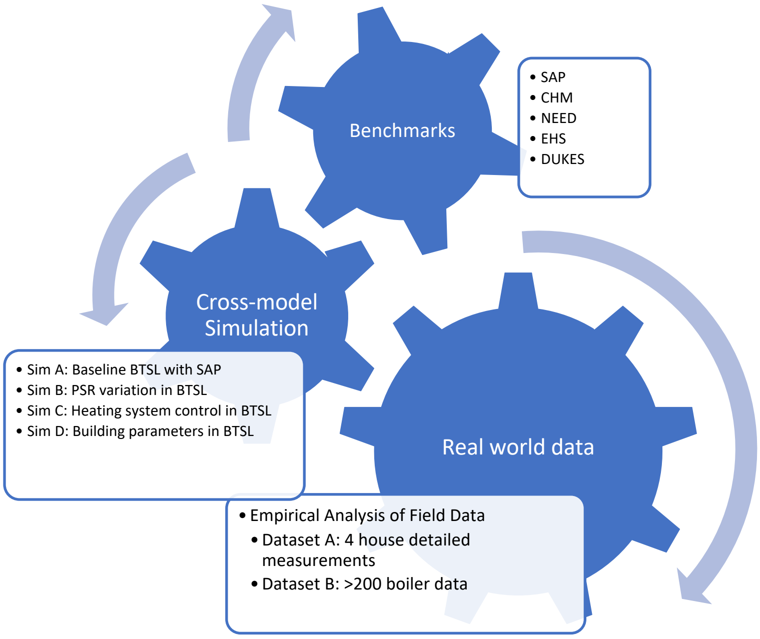


Figure 25: Overview of research structure

The outline of the cross-model comparison is as follows and involves firstly a single case study with parametric analysis, similar to that applied by Kokogiannakis (Kokogiannakis et al., 2008) for an office building case. In this first case analysis, the building is a fixed base in which various gas boiler variants can be simulated. The heating system input variables form a set of SAP input values which are either not considered in detail or crudely grouped together. This includes the heating system output (plant size ratio) and control system as these would not be considered indicators dependant on the heating system in SAP but only the building fabric. Simulation outputs and key performance indicators of mean internal temperature and delivered energy can then be compared across heating system variants. Then diving deeper into the boiler dynamics (a benefit of the chosen simulation environment to be expanded upon in the next section) to scrutinise power output levels, cycling, heating circuit temperature, delivered heat, and ultimately efficiency.

The cross-model comparison is then extended into the building parameter space by holding the heating system constant and varying building parameters in order to investigate whether the phenomena apparent in the initial cross-model comparison are present also in other building types and how they may vary when the building fabric changes. This is especially relevant in the context of building regulations and building construction trends which are driving the insulation and thermal mass of future dwellings.

Although the simulation model has previously been validated, as explained in the following sections, two types of field data are analysed by way of deepening the validation of the cross-model comparison as well as looking for new insights. To say that a model is ever fully validated would bely the complexity of building physics, the aim here is to increase the confidence in the model through exposure and comparison to more empirical data with more variables than previously. The data collection methods will not only include traditional temperature sensing and gas/electric meter readings but will be enhanced by high frequency diagnostic data from the heating system. The aim of this method of data collection is to allow new avenues for analysis of the interaction of heating system and building that have as yet not been exploited by the academic community. Comparison with existing databases will be done to place the collected data in a national context by looking at significant databases of residential energy use that exist for the UK, such as National Energy Efficiency Data-Framework (NEED) (DECC, 2016), Digest of UK Energy Statistics (DUKES) (BEIS, 2017a), Energy Follow Up Survey (EFUS) (DECC, 2014) and the Cambridge Housing Model (CHM) (Hughes et al., 2011) thereby strengthening the knowledge and tools in energy demand research to facilitate the transition to a low carbon future.

4.1 Dynamic Simulation Tool

The advantages of engineering models include the ability to simulate new technologies and their interactions (Swan and Ugursal, 2009), to get a detailed understanding of energy flows and temperatures. However, engineering models depend on detailed input information about technical performance of the building components and technologies, occupant behaviour and unspecified end-uses leading to potentially erroneous results (Lomas and Eppel, 1992) which can be exacerbated by the increasing number of input parameters (Chapman, 1991).

The BTSL (Building Technology Simulation Library) model is a fully dynamic engineering model with a library of simulation blocks such as archetypes of buildings, heating system components and users, which can be linked within the MATLAB Simulink environment; the interaction of these elements is shown in Figure 26. The BTSL model allows for modular creation of a building model whereby the heating system and building characteristics, user behaviour and weather can be varied. The advantage over other available models is the depth of detail at which a user can specify the heating system. Individual system components such as pumps, pipes and valves can be included, parameterised and physically modelled. In addition, the transient behaviour of the heating appliance is modelled through time response parametrization, control feedback loops and the associated control algorithms. The library of virtual components and simulation 'blocks' was already existing and in use within the Bosch development departments having been previously developed in house. This type of proprietary modular concept is used in industry to simulate heating systems under a number of installation environments and verify behaviour and control strategies. An analogous modular construction of simulation in the MATLAB environment with a TRNSYS Building model has been suggested by Rysanek and Choudhary (Rysanek and Choudhary, 2012) which served the purpose of evaluating the possible intervention options, building and HVAC system, available in a building upgrade situation.

BTSL operates as a co-simulation between TRNSYS building model and MATLAB based heating and user simulation. This type of hybrid simulation environment is also possible with the popular EnergyPlus (USDoE, 2018) building simulation software. The Building Control Virtual Test Bed (BCVTB) enables co-simulation of EnergyPlus with a number of other simulation environments including Modellica, MATLAB and TRNSYS. The aim of such co-simulations is to allow developers to extend the scope of simulations by adding simulation blocks of different types and depth to the central building model. The philosophy for BCVTB is as follows (Wetter et al., 2016):

> *"The BCVTB allows expert users of simulation to expand the capabilities of individual programs by linking them to other programs. Due to the different programs that may be involved in distributed simulation, familiarity with configuring programs is essential."*

BTSL has taken up the same co-simulation structure with the same aim and drawbacks as associated with the BCVTB by combining a known and stable building simulation core of TRNSYS within the MATLAB environment where competent programmers can code the physical and control behaviour of heating systems to the detail level they require, thus allowing benchmarking of new heating configurations, rapid development of new devices and controls as well as co-simulation of real hardware, so called Hardware In the Loop (HIL) or partial emulation.

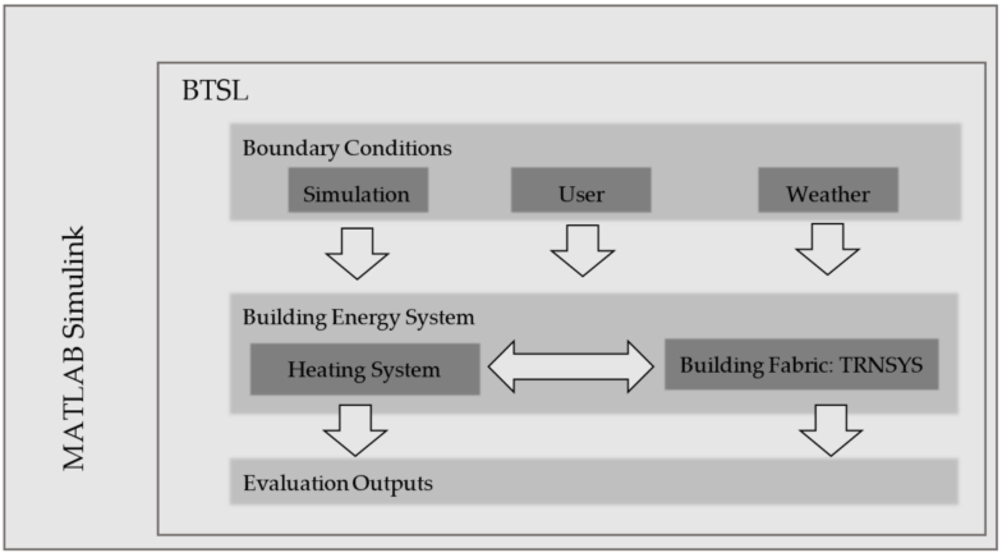


Figure 26: Schematic representation of hierarchy of BTSL Simulation Environment

The origin of BTSL is from a proprietary heating system emulation tool for product development at Bosch Thermotechnology, called Labhouse (da Silva and Knabe, 2003, Perrin, 2012) . Since its inception, it has been developed and expanded into the current BTSL library and includes a wide range of HVAC components such as radiators, thermostatic valves, boilers, cooling coils, fans and pumps. BTSL is designed to support the development of heating systems and their controls and thus has a high level of flexibility with regards to the heating system library block in Simulink but uses an existing building model, TRNSYS (Klein et al., 2010), to simulate the building fabric. The TRNSYS building model, known as "Type 56" is a modular transient system simulation program which meets the general technical requirements of the European Directive on the Energy Performance of Buildings, making TRNSYS a potential candidate for compliance with the directive's implementations in various EU countries. MATLAB Simulink has an open architecture that facilitates linking models developed in different programming languages, such as C, Java or FORTRAN, therefore enabling TRNSYS Type 56 building model to be implemented into the BTSL library, alongside the proprietary, MATLAB based, heating system blocks of Bosch Thermotechnology. The hierarchy of these various models and programming environments is shown in Figure 26.

BTSL is utilised in the context of this research as a means to explore how a fully dynamic SAP would reveal interactions between boiler dynamic, plant size ratio and controls. By first setting up the Base case within the BTSL environment in such a way as to mimic many, but not all the the assumptions of the SAP model, paving the way to introduce the dynamic aspects of heating in a controlled manner. The steady state values of the parameters in discussed in the following paragraphs illustrates the extent of the compromise that had to be made to mimic SAP within the constraints of the BTSL dynamic model structure. But as mentioned, the key simulation tool of 'ideal heating' was critical to this base case validation step.

All simulation blocks could be used directly from the available BTSL library[9] with only minor changes to the parameterisation to allow use in this study. This accounted for most aspects of making a dynamic version of SAP in BTSL, such as the dynamic weather, building and heating system models. However, the issue of gains, from electrical appliance use, cooking and metabolism, although dynamic in and adjustable in BTSL were identified as being suitable to set as constant with time. The 'user' block, which defines and calculates the user/occupant influence on the following parameters needed to be replaced to allow replication of the SAP standard:

- Metabolic heat gains
- Electrical appliance usage schedule
- Lighting heat gains
- Window opening schedule
- Domestic hot water usage schedule
- Internal temperature setpoints

A BTSL user behaviour profile was created, aligned to the calculation method of the SAP. The profile is parameterised automatically for the building under consideration due to inter parameter dependencies such as the number of inhabitants being proportional to the building floor area. This user profile contains the heating schedule and setpoint temperatures as well as the metabolic, electrical and hot water heat gains; internal gains were all matched according to Table 6 and Table 14. The user interface of the new block is seen in Figure 27. This regrouping of user boundary conditions (setpoint temperatures, metabolic gains) and internal gains into one BTSL block was a necessary adaption of the BTSL structure to accommodate some of the simplifications of the SAP calculation method and focus on heating system dynamics. In the BTSL user block the complete user profile was defined and could be varied independently of all other blocks, but SAP methodology derives user and solar driven gains on the basis of the building alone (floor area and window properties respectively). For example, where previously the BTSL user block profile would allow the choice of the number of inhabitants as an integer and calculate therefrom the metabolic internal gains, the SAP procedure calculates a theoretical number of inhabitants based on floor area, therefore allowing

[9] Access granted through the sponsorship agreement with Bosch

fractions of persons in a similar vein to the British average family with 2.4 children alluded to in TV comedy[10].

Similarly, the setpoint temperatures are defined in part on the building characteristics (namely the HLP), the lighting gains are defined on the available sunlight and therefore the window and shading conditions. Therefore, it was decided to include these parameters here in the SAP user block as inputs where they could not be directly called from the other model blocks (as was the case for Building floor area). In summary, all relevant parameters for these gains are then summed as direct thermal, temporally constant gains.

[10] 2point4 children (1991-1999) http://www.imdb.com/title/tt0101032/?ref_=fn_al_tt_1

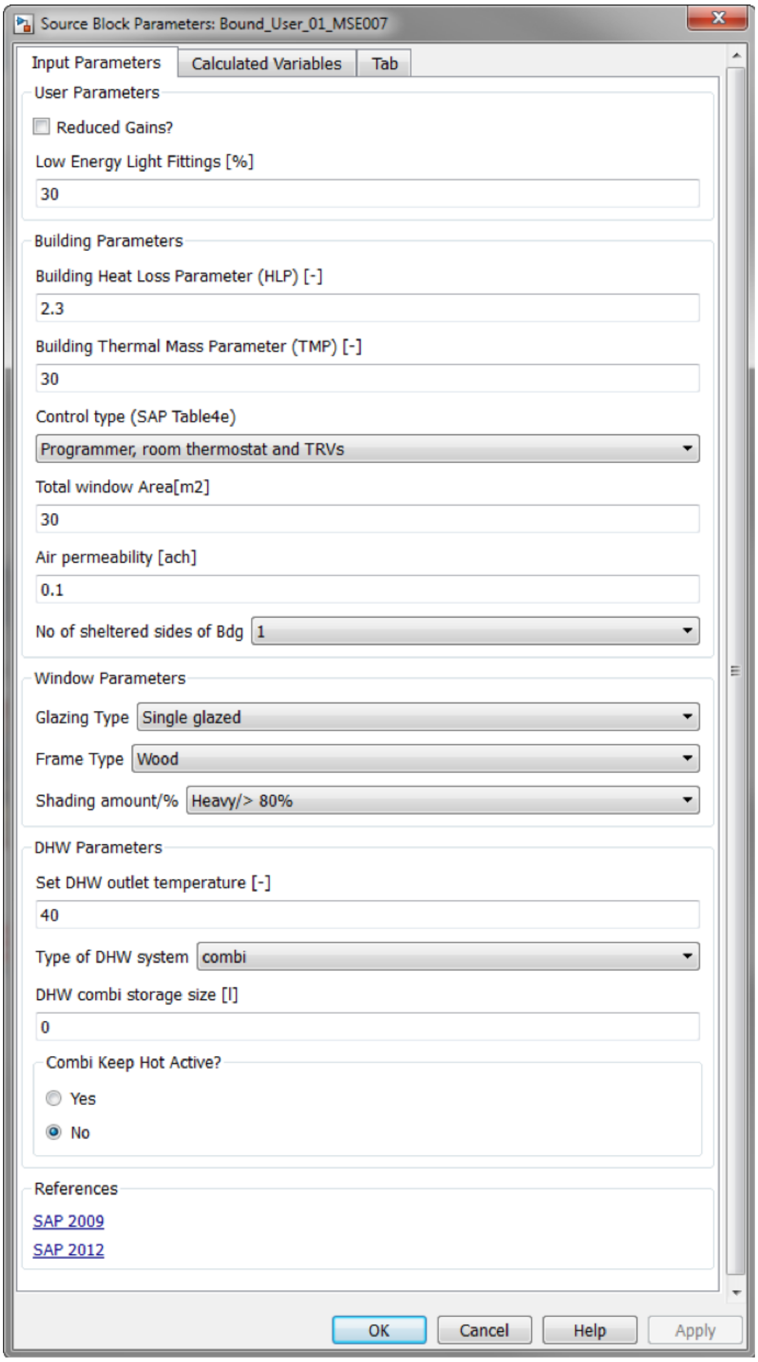


Figure 27: User interface of SAP User block in BTSL

4.1.1 Dynamic Model Parameterisation

In the first phase of the research an existing test case (full SAP calculation worksheet with all input and output data) was used to compare normative SAP model with the dynamic BTSL model. In this case, the relevant parameters are taken directly from the test case, which includes all relevant input parameters for a SAP calculation, but not necessarily all parameters, or at least in the same detail or format, for BTSL. The detailed summary of the BTSL building input parameters are documented in Appendix D. These were chosen and iteratively tuned to achieve the same high-level heat loss and thermal mass as specified in the SAP test case (Appendix B) such as how to model SAP monthly average internal gains into the BTSL dynamic simulation environment while balancing physical dynamics, representation of SAP and comparability e.g. gains from hot water implementation in the time domain.

The dynamic BTSL model requires hourly external temperature profiles, rather than the monthly averages used in SAP; a weather data file from the US Department of Energy was used (USDoE, 2013), the location of which was chosen to best replicate the location of the test case building, in this case at Finningley, UK. The annual average heating season external temperature difference between that assumed by SAP and the Simulink weather file is <0.7K (for heating season, SAP 6.81°C, BTSL 6.18°C). Additionally, because SAP uses only the outdoor air temperature to calculate the heat loss to the environment (whereas BTSL uses also the ground temperature for the loss through the ground floor and basement) the Simulink model was altered to link the air and ground temperature, so that the air temperature was used as the external temperature regardless of the external surface position or type.

Table 6: Summary of Dynamic Parameters in BTSL and SAP models (X=dynamic, -=monthly constant value)

Parameter	BTSL	SAP
Metabolic Gains	-	-
Electrical Gains	-	-
Hot Water Gains	-	-
Solar Gains	X	-
Air Exchange	-	-
Outdoor Temperature	X	-
Indoor Temperature	X	-

Zone setup in SAP is differently implemented in BTSL due to the 5 Zone structure of the building model. Therefore, Zone 1 is matched by size and location since this is the living space and leading in the consideration of comfort and space heating. Zones 2 to 5 were set at the same temperature in BTSL.

Since SAP assumes an instant response to heating, BTSL was run firstly with an 'ideal heating' system to allow direct comparison. The 'ideal heating' system has no thermal mass or physical representation in the model other than delivering heat instantaneously into the building via an 'active' layer at the wall internal surface. By using the 'ideal heating' function of BTSL the remaining blocks, especially the building block, are calibrated to the test case data on the basis of internal temperatures and delivered heat energy. Ideal heating effectively disables the detailed heating system parts of the simulation and operates a direct, undelayed heat input into the building model zones.

This ideal heating system is approximated as closely as BTSL allows to the instantaneous response heating assumed by SAP. it was implemented by modelling heat input to the building zones without a normally defined heating system, but with heat delivered through a zero thermal mass active layer in the building virtual fabric. In this manner, the heat input will exactly and instantly match the requirement of the building up to a limit of 3.5kW per zone, resulting in a near instantaneous rise of internal air temperature to achieve the set-point.

For clarity of discussion it is worth describing one aspect of the complex BTSL simulation model, namely the treatment of radiant and convective heat transfer from heat emitters and walls to the internal air. The marriage of TRNSYS and MATLAB models in BTSL preserves the interface between the TRNSYS building model and the heating system components which separates walls from a single air node for that zone. Components transfer heat between the air and the walls and radiators are calculated every timestep and the air, and wall surface temperature updated accordingly. For the purposes of this analysis it is worth noting that this a) leads to a disparity between the zonal air temperature and the associated building elements and b) the walls and radiators heat transfer is calculated both for radiative and convective pathways.

4.1.2 Simulation input parameters

Following the ideal heating base case, a series of representative heating systems were introduced into the BTSL model to investigate the theoretical impact of different heating system parameters. A wet radiator gas fired boiler system was modelled, which included thermostatic radiator valves and utilised a system parameterised with laboratory data from the manufacturer Bosch: a Greenstar iJunior boiler (Bosch, 2009), since replaced by the Greenstar i (Bosch, 2015a), both of which include the same main heat exchanger.

Table 13 summarised the parameter items under investigation in the BTSL model covering the variables related to the heating system that are assumed to have no influence on MIT according to SAP. In the case of heating controls, SAP considers that having no control or basic controls will affect the MIT (not considered in this research), otherwise more sophisticated controls are considered to improve the efficiency. Heat up optimisation is a common function on heating system controls which aims to achieve setpoint temperature by the specified programmer time; the user can expect the room to be at the desired temperature when the heating period starts, therefore eliminating any delay due to the responsiveness of the heating system or building thermal mass. The simulated control types all are comparable to the SAP test case description of 'Room Thermostat' i.e. the variables altered in BTSL do not alter the calculated SAP temperature or energy from that used in the base case.

4.2 SAP Calculation & EPCs

SAP is the NCM against which dynamic model results will be checked in order to uncover weaknesses or inconsistencies in the assumptions and methodology surrounding the dynamics of heating systems in buildings.

At the outset of this thesis the current version of SAP was SAP 2009 (DECC, 2009) with SAP 2012 and RdSAP becoming fully implemented later in 2014 and 2015. The basis for comparison in this thesis is SAP 2009 while recognising the changes with respect to SAP 2012:

- Updated climate data
- Altitude dependent external temperature
- Updated CO_2 emission factors, fuel prices
- Extended losses option for primary pipework

The above listed changes do not affect the core methodology of SAP, which this thesis seeks to investigate. The test case SAP calculation was an existing test case calculation performed using SAP2009 worksheet v9.9; the input data and calculation results are included in the appendix B.

4.2.1 Cambridge Housing Model

There is a UK housing stock model which, using English Housing Survey (EHS) data (DCLG, 2017) and SAP 2009 methodology estimates CO_2 emissions for all homes in England. This is the Cambridge Housing Model (CHM) (Hughes et al., 2011), an Excel based model developed by Cambridge Architectural Research Ltd for DECC (currently BEIS) to replace BREHOMES as a national housing energy demand model for assisting retrofit scenarios and to inform policy decisions. Comparison against other data sources of energy demand has been carried out to validate the applicability of the model (Palmer et al., 2013). In this thesis CHM is used as a detailed database of UK building energy demand to assess the representativeness of the data collected from the field both in terms of heating energy demand but also plant sizing since the CHM gives an estimate of the current state of the fabric heat losses of English housing stock.

4.3 Data Collection

Data collection within this project centred on two sources. On the one side a detailed monitoring of 4 individual dwellings (Empirical Dataset A) setup and monitored during the research program and on the other side a wider dataset of 221 (filtered from 259) dwellings focussing solely on boiler diagnostic data (Empirical Dataset B) coming from an existing monitoring program within Bosch. The details of both datasets are described below.

4.3.1 Ethics

Before commencement of data collection, the ethical implications of the program of research were considered and adhered to as per the formal UCL process. Due to the planned uses and nature of the data to be collected (heating system and temperatures) and its form, an exemption from ethical approval by the ethics committee was documented and approved. The data would be in the form of existing anonymised datasets from Bosch Thermotechnology and additional monitoring within the Bosch Field Trial system with an additional signed agreement with the building inhabitants/owners to document informed consent. The imperative when collecting and handling the data within this research was to ensure anonymity for the building occupants and prevent the release of occupant specific data into the public domain. Direct monitoring activities as carried out by the researcher for Empirical Dataset A were done with the strict consent and knowledge of the residents (in all cases residents were owner-occupiers), implications during and after the measurements period were explained and accepted by all participants by means of a signed release form (see 9.6 Appendix F: Informed consent form). Empirical Dataset B was pre-existing at the start of the research period and had been collected by Bosch Thermotechnology as part of an ongoing project for internet connected heating appliances. The data was already anonymised when received by the researcher, in that individual boiler data was designated with a specific boiler gateway serial number only, with no address or occupier data.

4.3.2 Boiler Diagnostic data: EMS bus

A common and novel feature of the data collected in this thesis is the EMS (Energy Management System), the proprietary bus communication protocol within the Bosch Thermotechnology Group. EMS is the internal heating appliance communication protocol containing the pertinent parameters for control and regulation of the system operation. This can be within the appliance itself, with room and system controllers as well as (most recently) via IP connectivity to a remote server and from there to mobile applications and algorithms. Historically this bus was also used for diagnostic and development work before later being made available to service engineers so they can interrogate the heating system controls. In addition to operating parameters, EMS carries failure codes which could be displayed (on a boiler-mounted or room controller display) or read by the service engineer using special software. These codes are generated by the control board when fault situations are deemed to have occurred by the internal software, for example when values exceed predetermined limits (showing faulty operation or a faulty sensor) or rates of change. Detection of the fault will lead to one of three conditions of the boiler. The boiler may continue to operate normally while displaying or logging the fault, the boiler may go into a temporarily blocked state where a reset from the user is required or, in the case of safety critical or repeated faults, the boiler may go into total lockout without the possibility of a manual reset. Whether resetting the appliance or, in safety critical cases, complete blocking of operation, the associated fault codes are logged and can help in the subsequent fault-finding activities by the service technician.

Although a detailed definition of the communication protocol exists within Bosch to ensure interoperability of the products, it is a proprietary system and is considered commercially sensitive and therefore cannot be fully published here. However, in general terms the EMS system contains a large number of parameters in order to cater for a wide range of heating system configurations and product variants. As such the subset of parameters relating to combi boilers is limited but even this small subset can vary across a product range depending on available sensors and functionality. The core parameters which are common to most boilers are listed in Table 7.

Table 7: Boiler parameters available on EMS

Variable Name	Description	Unit
Actual Power	Current burner power modulation, 0 – 100 %	%
nominal maximum Burner Power	Nominal burner power (maximum heat output)	kW
Actual Pump modulation	Current circulating pump speed modulation level, 0-100% (regardless if a modulating pump is present or not)	%
Date	Recorded date, Format: dd-mm-yyyy	-
Time	Recorded time, Format: HH:MM:SS	-
Heat Request Status CH Frost **Heat Request Status CH EMS** **Heat Request Status Switch**	ON/OFF Flags for CH heat request coming either from frost temperature alert, a connected EMS or the room thermostat switch	-
Heat Request Status DHW Frost **Heat Request Status DHW EMS** **Heat Request Status Internal Detection**	ON/OFF Flags for DHW heat request coming either from frost temperature alert, a connected EMS or internal DHW flow detection	-
Supply Temperature **DHW outlet Temperature**	CH supply temperature, measured by boiler Domestic Hot water temperature measured leaving the boiler	°C
Working Time total Burner **Working Time CH** **Working Time DHW**	Total working time of boiler, working time of boiler for CH or DHW heat supply, recorded by boiler control system	min
Number of Burner Starts **Number of Starts CH** **Number of Starts DHW**	Total number of burner starts / Number of burner starts for CH or DHW heat supply, recorded by boiler control system	-

The data streams internally, are collected at the boiler control board, as either direct sensor measurements, status signals, combined data or calculated parameters (such as aggregate working time). As such the accuracy of the measurements can be subject to the tolerance of the components used in the production, as is the case of temperature sensors for water mounted to pipes and heat exchangers, where an accuracy of ±2°C is referenced by the manufacturer. For actual power the value recorded is the 0-100% modulation level calculated by the boiler control board which is then translated into a fan speed to regulate the gas/air volume, as is standard in modern condensing premix boiler systems. The control of the fan is normally achieved by means of a feedback loop between the boiler control and on-board fan electronics, the current speed of the fan is measured using a hall sensor and the interpreted signal sent back to the boiler control with an estimated accuracy of ±200rpm across a range of approx. 5000rpm. The central heating circulating pump control also operates in a similar way to the fan, although whereas modern boilers all operate a modulating fan to control thermal output, not all have a modulating pump. When present, a modulating pump can be speed controlled, to modulate heating circuit flow rates, but fixed speed pumps are still common and would simply be turned on or off with the possibility of adjusting the speed via a manual switch on the pump itself. However, these tolerances can only be used as guidelines since the detailed boiler component data is company confidential and only general figures are quoted here.

The data collected is not recorded at a fixed time step but only sent from the boiler when a parameter changes, this method has been implemented by the manufacturer in the boiler software to reduce the total data volume transmitted and therefore the load on the homeowner's internet connection, but the logging server reinstates the missing timestep information according to the previously logged value (fill forward), to allow the recording of fixed timestep (5 second) data with no loss of integrity, which is then made available for download as comma separated values 'csv' files.

For dataset A, where 4 houses were monitored, the EMS data and additional sensor data files were imported into Tableau software (Chabot et al., 2003) for visualisation and analysis, simplifying the process of meshing multiple data sources with different sample rates.

For dataset B where the data volume was considerably more than dataset A, the EMS 'csv' files were imported into MATLAB for filtering, collation, analysis and visualisation, conversion from csv into the native MATLAB '.mat' files was necessary to reduce the file size and respective load times to a practical level to be carried out on a desktop PC. Initial visualisation of individual boiler logfiles and prototyping of the analysis algorithms was carried out on an individual desktop PC, enabling fast debugging iterations, before utilising the greater processing power of the Bosch High Performance Computing-cluster (HPC), based on Bosch premises near Stuttgart, Germany, to analyse all boiler logfiles and collate the results.

Qualification for a boiler dataset to be included in the Central Heating (CH) assessment requires the duration of the log file to be at least 12 months long. On average 404 days are recorded per boiler. Also, as is common with remote datalogging activities, data loss and corruption are issues. A number of pre-processing filter steps were carried out to ensure that unreliable data was excluded from analysis, this included the following pre-processing filters for all data files:

- Check channel data within expected limits E.g.
    - Actual Power 0-100%
    - Hot Water Flow Sensor Turbine
- Heat Request Status Internal Detection has to identify the DHW demand (i.e. Flow turbine measurement & DHW outlet temperature)

Data redundancy is a feature of field monitoring which is desirable but not always financially or practically possible (section 2.1 (Lowe et al., 2017b)). The advantage of multiple channels of data coming from the boilers is that logic checks could be carried out to verify certain aspects, for example, a central heating demand flag is sent as a Boolean, but at the same time, the burner must fire, the pump and fan must run and last but not least the central heating water temperature directly exiting the heat exchanger must rise (analogous to the boiler internal diagnostic checks performed with the same data). Similarly, for domestic hot water, but with the addition of the flow turbine sensor and hot water outlet temperature signals. Together these signals provide a level of internal redundancy which was used in the analysis to corroborate the existence or false logging of heating and hot water demands. Similar corroboration of signals is used by the boiler internal software for error detection.

4.3.3 Empirical data A: Building & Heating System

A deeper empirical study was carried out to collect data from three UK houses and one German house, all with gas boiler technology as the main heat source, however differences exist in the building typology, heating system and measurement strategy employed. Buildings were sought which could provide measurement data from gas heating systems in residential buildings which could partly be representative of the wider UK housing market context. Key practical requirements for the building was that it should have a Bosch boiler which can report the internal EMS data via the addition of a Weblogger in the dwelling.

The main features of the buildings, heating systems and measurement strategy are shown in Table 8:

Table 8: Building properties summary UK1-4 & DE1 (- indicates unknown or undisclosed)

Building	UK1	UK2	UK3	DE1
Location	Oxford, UK	Oxford, UK	Worcester, UK	Stuttgart, DE
Occupancy	2 adults, retired	2 adults, working 2 children	2 adults, working 1 child	2 adults, working
Building Type	Detached House	Detached House	Detached House	Semi-detached
Heated Floor Area	106 m^2	111 m^2	87 m^2	122 m^2
Heated Floors	Ground, First	Ground, First	Ground, First	Basement, Ground, First, Second, Attic
Age, approx.	1910 (2004 extension)	1980	1850	1960
Construction Type	Original Solid brick Extension cavity wall	Cavity wall	Solid brick	unknown
Insulation	Partial cavity	Partial cavity	-	80mm External
Window type	PVC double glazed	PVC double glazed	PVC double glazed	PVC double glazed
EPC Rating	E47	D63	-	-
EPC Energy Use	401	224	-	-

A key feature of all monitored houses is their reliance on a main gas fired heating system, the main features of which are listed in Table 9.

Table 9: Heating system properties summary UK1-4 & DE1

Building	UK1	UK2	UK3	DE1
Central Heating (Datasheets in Appendix)	Gas Combi Boiler Greenstar CDi Classic 8-42kW DHW 8-31kW CH	Gas Combi Boiler Greenstar i Junior Combi 7-28kW DHW 7-24kW CH	Gas Boiler Greenstar i System Compact 7-27kW	Gas Boiler Buderus C9000WM (Bosch brand) Modulation 1:10 2.5-25kW
Secondary heat source	none	none	Solar	Wood stove 5kW Solar
Hot Water Tank	none	none	250litre unvented	210litre stratified
Emitter type	Radiators	Radiators	Radiators	Radiators * 9 (Basement * 2, Ground * 3, First * 3, Attic * 1)
Emitter heat transfer capacity (ΔT 50C)	21.9kW	11.3kW	12.6kW	unknown
Controller	ON/OFF Room thermostat	ON/OFF Room thermostat	Smart thermostat	Modulating room thermostat
Weather Compensation	none	none	Yes	Yes
Thermostatic Radiator Valves	Yes	Yes	Yes	Yes
Solar Water Heating	none	none	Yes	Yes

Data recording was performed using two distinct but complementary methods:

- Remotely monitored via IP connectivity
    - Boiler diagnostic data from EMS communication bus
    - Gas and electric meter data
- Locally recorded
    - Temperature sensors (Tiny Tag and HOBO)

The deployment of the measurement equipment varied between the case studies and is summarised in Table 10.

Table 10: Data types recorded at properties UK1-4 & DE1

Building designation ->	UK1	UK2	UK3	DE1
Boiler diagnostic data	X	X	X	X
Outdoor temperature	X	X	X	X
No. of indoor temperature.	9	9	5	5
Building level gas & electric consumption	X	X		
Solar Radiation (Horizontal)	X			

The boiler communication bus (EMS) was connected to a Bosch 'Weblogger' (Data-Ahead, 2017) in order to buffer and transmit the data via an ethernet internet connection via the homeowner's router to a remote server at Bosch subcontractor Data Ahead, from which the data could be interrogated and downloaded at any time. Additional wired inputs are available on the weblogger which were partially utilised to connect temperature sensors and a pyranometer (UK1 only). Temperatures measured on the weblogger used Type K thermocouple and the pyranometer was connected to the general purpose 0-20mA connections available on the weblogger, as shown in

Figure 28.

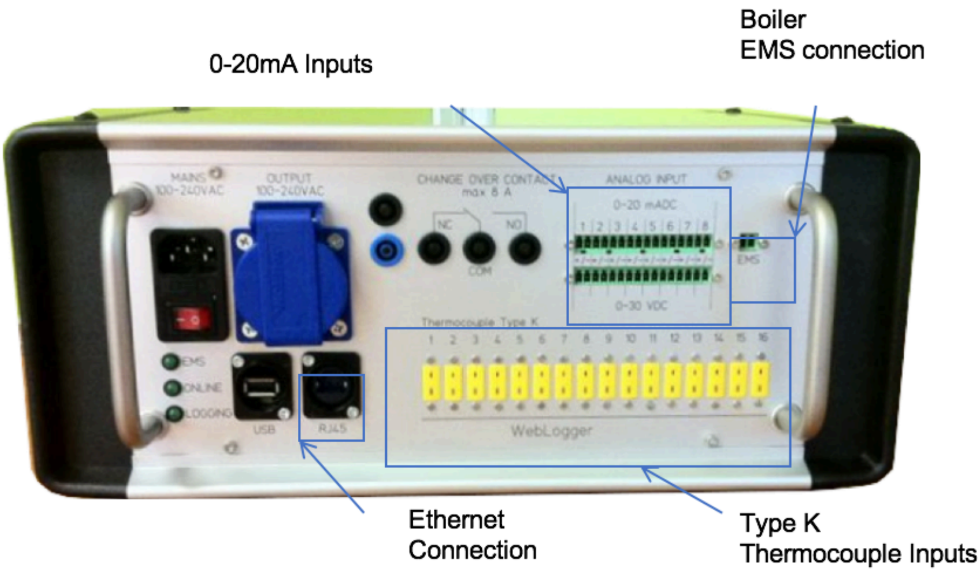


Figure 28: Weblogger input/outputs

The EMS data stream, as described in more detail in section 4.3.2, is a bus system with no fixed sampling rate but only transmits a parameter value when it changes. However, the frequency at which the system checks for changes is such that the effective sampling rate recorded at the server is 5 seconds. Recorded and live data can be interrogated via a secure (username and password protected) web browser interface provided by Data Ahead. Several screens are available such as the live data stream shown for the datalogger at UK1 in Figure 29. It is important to point out that although the boiler control module and the EMS bus are continuously reporting all the internally logged parameters, the channels that should be logged by the weblogger server need to be manually selected via this web interface in order to be stored and available at a later date. The channels selected can vary depending on the boiler type connected and the details of what was logged for the different houses will be discussed later, but the main aim was to cover the main boiler operating activity and therefore the data and events listed in Figure 29.

An additional key feature of the weblogger system helps to avoid unwanted data dropout. Firstly, as mentioned, the data can be interrogated live via the web interface, however this relies on the researcher logging in and manually checking the data on a regular basis which is not always possible or practical. Therefore, a secondary system is in place whereby each datalogger must be assigned an owner whose Weblogger username and personal email address is known. Should the weblogger at the property lose connection to the server and not report any data for a period of 24 hours (roughly the timescale allowed by the internal weblogger buffer memory) then an email is sent to the responsible owner informing them of the issue. Although this cannot help to alleviate all issues with the datalogging via the weblogger, it can and did help to resolve issues with simple internet connectivity issues where a router reset easily corrects the issue.

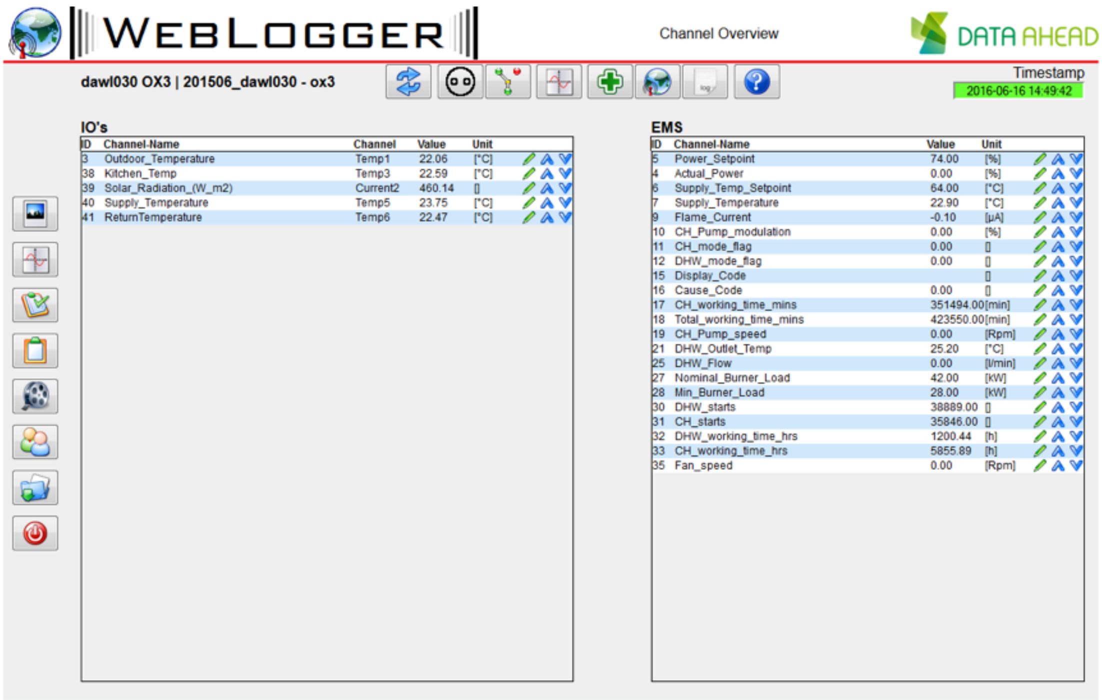


Figure 29: Screenshot of Weblogger browser interface

The logged boiler data just described was augmented by additional temperature sensors placed within the houses. A mixture of HOBO U12-012 (Table 11) and TinyTag (Table 12) sensors were used (full datasheets in Appendix). These were set to a sample the temperature at 15minute logging intervals. Placement of the sensors was by the researcher for UK1 and 2 and by the home owner (with guidance from the researcher) for UK3 and DE1. Both are small and unobtrusive enough to be placed in discrete locations. Placement was one sensor per room to cover the main living spaces and as much of the heated floor area practical. Attention was paid to ensure sensors were at mid wall height, away from radiators and other sources of heat, and out of direct sunlight. HOBOs are capable of measuring temperature, humidity and light intensity, a summary of the capabilities of the HOBO sensor is in Table 11. This monitoring campaign was designed to supplement the boiler data in such a way as to enable analysis of the heating response in the building and, with the aid of mean internal and external temperatures, the heat loss coefficient.

Table 11: HOBO U12-012 datasheet summary

Memory	**43,000 measurements**	**Sampling rate 1 second to 18 hours**
Temperature Range	-20° to 70°C (-4° to 158°F)	
Temperature Accuracy	± 0.35°C from 0° to 50°C	
Temperature Resolution	0.03°C @ 25°C	
Humidity Range	5% to 95% RH (non-condensing)	
Humidity Accuracy	±2.5% from 10% RH to 90% RH typical to a maximum of ±3.5% including hysteresis at 25˚C (77˚F)	
Humidity Resolution	0.05%RH	

TinyTag temperature sensors were mainly used for the remaining temperature measurements (see Figure 31). These sensors were developed to log temperature during product transportation, and therefore are small and rugged in design, importantly in regard to external environmental factors such as water ingress. The sensor can only be initiated and data extracted via a proprietary inductive plate. The model used during this research is a variant on the Transit 2 model, which differs in that it takes a larger, and therefore longer lasting, button battery.

Table 12: TinyTag datasheet summary

	**Memory**	**>25000 data points**
	Temperature Range	-40 to +70°C
	Temperature Accuracy	0.4-0.7°C
	Temperature Resolution	0.01°C

UK1 and UK2 were both fitted with energy meter logging equipment from Navetas under the brand name ‘Loop energy Saver’ (Navetas, 2017). These retrofittable, non-intrusive measurement devices are mounted externally to the gas and electric meters (Figure 30) and transmit the data via the homeowner’s internet connection to the Loop server. Gas consumption is registered by the building gas meter and the loop sensor optically recognises changes in the final digit of the meter display. Therefore, gas consumption logged by the Loop sensor should give a direct recording of the gas meter reading, but issues of data loss should be considered. The building level electricity measurement is carried out using the loop current clamp which is attached to the live cable from meter to building. Drawbacks of the electrical power meter from Loop concern the power factor (ratio of real to apparent power). The presence of multiple inductive loads in the building electrical appliances, such as motors in washing machines, can lead to a decrease in the power factor and therefore a larger discrepancy between the real electrical energy consumed and that measured by the Loop current clamp. Since no detailed assessment of the building electrical loads was performed, electrical consumption data taken from the Loop sensor will mainly be used for qualitative indication only, such as occupancy or activity levels, with the main focus remaining on the gas consumption.

Figure 30: Gas (left) and electric (right) meter reading devices from Loop

Although every effort was made to ensure a coherent and seamless recording of measurements, logistical and technical issues led to staggered commencement of data collection and gaps in the timeline. The overview of data streams and sensor data recording is shown in Figure 31.

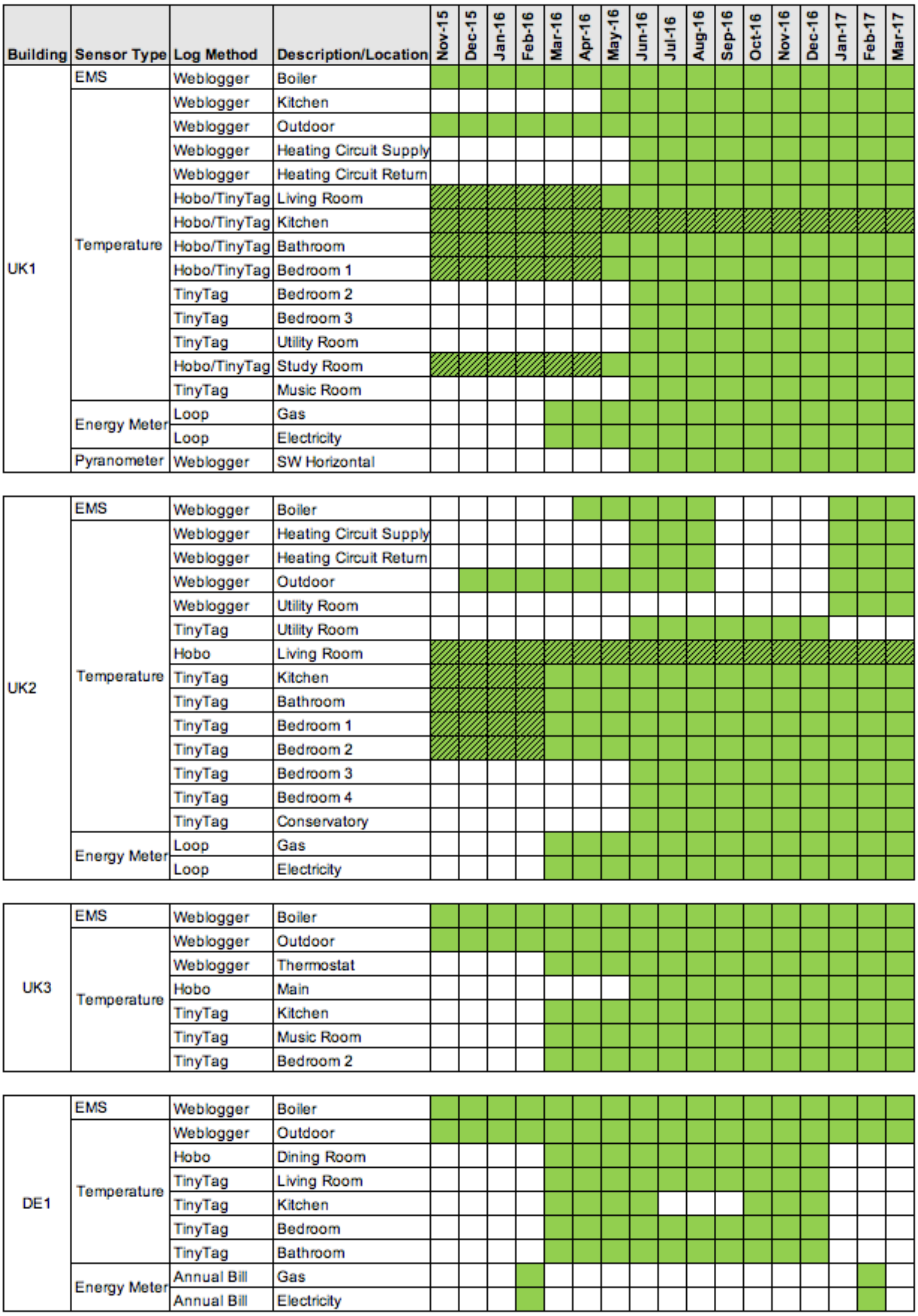


Figure 31: Data map showing data availability over time for monitored houses (green indicates active measurement, hatching indicates period where a HOBO sensor was used)

One technical failure occurred at building UK2 during the measurement period where the weblogger was offline between August 2016 and Jan 2017, during this time period numerous attempts were made to repair the hardware in this period, without success, before replacing the complete unit in January 2017.

4.3.4 Building heat loss estimation

The research conducted in this thesis looks at the interaction of heating system and building and, while much information about the heating system can be gleaned from the data streams and direct observation of the system in person, derivation of the building fabric can be more difficult and has been shown to be a major contributor to the performance gap (Stamp, 2015, Johnston et al., 2015), and direct measurement is a key tool to understand the real situation (ZCH, 2014).

In order to assess the total heat loss of the buildings under investigation the Power Temperature Gradient method was employed to derive the heat loss over different external temperature and weather conditions (Summerfield et al., 2015), continuing in the tradition starting from PRISM (Fels, 1986) and following on from recent work using smart meter (Chambers, 2017) and disaggregated heating system data (Farmer et al., 2016) to estimate HLC.

Since the data collection framework of Dataset A includes, as a minimum, indoor/outdoor temperature and boiler EMS with supplementary gas/electric meter data in 2 houses, then the desired data types are present for a PRISM style power temperature gradient to be plotted. By first using metered energy input, in the case of UK1 and UK2 buildings, a baseline can be made before investigating methods to disaggregate heating/hot water thermal input via the EMS boiler data stream, enabling common boiler data based Power Temperature Gradients (PTGs) to be made for all 4 houses under observation and following a similar methodology to the integrated heating test (Farmer et al., 2016),. Because the utilisation of boiler diagnostic data such as EMS for the PTG and building heat loss estimation is an, as yet, untested method, the details of the iterations and decisions made in developing the methodology are described in the results section with the aid of data visualisation from the intermediary steps. How the boiler EMS data can be manipulated to extract disaggregated energy consumption information is expanded upon in the next section since it is common to Dataset A and B.

4.3.5 Empirical data B: Combi-boiler

The limitation regarding the data collection in Dataset A is primarily the small selection of buildings, therefore the empirical study was expanded and the larger Dataset B was collected. As part of the research it was possible to gain access to a larger dataset of boiler diagnostic data from combination boilers produced at Worcester Bosch.

A download of boiler data logged from February 2014 to August 2015 was made available as csv files, one per boiler. Each boiler records a total of 109 variables. In total control data from 338 boilers was collected, however due to the cross-checking criteria, only 221 could be used for the analysis of central heating data (as described in section 4.3.2). 117 boiler data files were discarded due to one or more of the following reasons:

- Measurement period less than one year
- Missing data periods
- Missing parameters

Gas consumption by the boiler was derived using the actual power level, expressed in 0-100% modulation and the known nominal maximum Burner Power, which was then summed over the time period where the respective CH or DHW flag was active, thereby distinguishing between heating and hot water energy consumption. This is an approximation for the gas consumption of the boiler and not a direct measurement thereof, although the boiler modulation level follows the fan speed closely, the exact volume flow rate of gas which is fed to the burner as a result of the fan controlled pneumatic gas valve depends also on the inlet gas pressure at the valve, this pressure is not measured and therefore remains unknown, although it should not be outside the range 19 - 23 mbar at the gas meter and 16.5 - 20.5 mbar at the boiler gas valve, taking into consideration gas pressure losses within the building (Bosch, 2009).

Although this dataset can claim to offer a considerable amount of data with regards to the heating system behaviour, Dataset B is limited in some key ways. Foremost, the sampling is such that the representativeness is unknown. All measured parameters have been reported by the boiler itself with no other sensors connected in the houses and no visits were made, therefore external corroboration is not possible, for example in the same way as the boiler energy consumption can be compared with gas meter readings in Empirical Dataset A. Due to the anonymising in the data collection between IP module and the database to which access was granted, no link can be made to location, building type or any other data source which could shed light on the energy consumption in relation to building type or construction. However, the data does still provide a valuable opportunity when placed in the context of the simulation and detailed monitoring carried out as part of this research program. All boilers considered can be classified based on the boiler type and power output, and due to all the boilers being combination boilers, the domestic hot water and central heating can be easily disaggregated (as is also possible in Dataset A), at high frequency due to the 5 second logging timestep.

The dataset, whilst not representative of the wider building stock, does allow the investigation into a wider set of boilers and provides complimentary insights to simulation. Through the larger number of dwellings considered, any phenomenon seen in the simulations or detailed monitoring can be sought out and judged to be either isolated or more widespread. Due to the high proportion of combi boilers in the sample a deeper insight into the DHW behaviour of the households can be observed as well as general trends in CH behaviour in so far as can be determined without building/occupant meta data.

4.4 Methods summary

As an overview of the main groups of results derived from the methods described in the previous sections. The mixture of methods and the varied scale and type of data available is advantageous in unpicking the detail of heating system dynamics from different angles and draw more robust conclusions. Table 13 shows the respective parameter spaces covered and a short explanation of the pertinent details.

Table 13: Simulation and empirical parameter space

Section	Parameter space	Notes
Simulation Set A	Baseline	Single building: ideal heating only Used for model calibration and baseline
Simulation Set B	Boiler rating, Plant Size Ratio	Single building and heating system design: variation of heating system size
Simulation Set C	Control	Range of control types • ON/OFF Room Thermostat • Modulating Room controller • Heat up optimisation functionality
Empirical Dataset A	Detailed Monitoring	4 houses with detailed measurements over 6+months
Empirical Dataset B	Boiler Data Only	200+houses No building or occupant meta data available

5 Simulation results

The following sections present more detail on the results of both SAP calculations, dynamic BTSL simulations. The details of the BTSL model and the setup and adjustments made for the simulations performed are to be found in section 4.1. All simulations were made to cover a one-year period. The simulation results will be shown based on the key parameters of internal temperatures and overall heat requirement. Aggregated time periods of month and year will be presented in addition to individual days selected for presentation. Results will be presented using time-based plots of internal temperature and heat system input contrasted with other gains.

The heating period under consideration in the investigation was October to April, although SAP considers the heating period to last from October to May. May was excluded from the comparison to help focus on the winter heating response rather than the transitional months, thereby focussing on the differences in heating system modelling and not on transient response during the transitional months. For the simulated example building the heating was only required for a few days in May and the overall contribution to the annual space heating requirement is less than 3%. A more detailed analysis of the winter-to-summer transition periods with regards to dynamic effects could be the subject of further investigation.

MIT (Mean Internal Temperature) is used by SAP as a key determinant of the overall space heating requirement of the building, therefore this parameter is calculated from the dynamic simulations for comparison with SAP predictions of MIT. More detailed time-based plots of the internal temperatures were made in order to understand the possible reasons for any differences relative to the SAP benchmark. Furthermore, the space heating requirement of the building was calculated from the heat flow from the boiler entering the heating circuit therefore bypassing issues of boiler efficiency at this stage. The space heating serves as a secondary way of verifying the difference between the EPC/SAP model and the more complex BTSL.

5.1 Simulation A: Model Comparison & Baseline

This section will lay the basis for a robust comparison of SAP and BTSL calculations and cross validate the models to build the confidence necessary to then draw conclusions from further BTSL results from simulations with varied parameter inputs.

The basis for the comparison is a SAP calculation for a sample house, which contains both input and output data. The chosen test case is a detached two storey house with an above average standard of efficiency (C80 rated EPC) the abbreviated designation for this building is SAP_GB. The input data used for both the SAP and BTSL models is summarized in Table 14, full data is available in the appendix C.

Table 14: SAP_GB Main Characteristics

Parameter		Value	Unit
SAP parameters (see section 2.6.2.1)	HLP (Heat Loss Parameter)	1.3652	W/m^2K
	TMP (Thermal Mass Parameter)	283	kJ/m^2K
	TFA (Total Floor Area)	100	m^2
Living Area (Zone 1)		30	m^2
Window Area		23	m^2
Window Orientation		East	-
Main Heat Source		Gas Combi Boiler	
Boiler efficiency (SEDBUK Rating)		90	%
Heating System Emitter Type		Radiators	-
Heating System Control		Programmer, Room Thermostat & Thermostatic Radiator Valves (TRVs)	-

Differences between SAP and the BTSL model result primarily from the additional complexity of the latter model to support a more detailed and dynamic simulation of the dwelling system, requiring a higher number of input parameters such as the heating system components and full internal / external wall construction materials and dimensions. It was necessary to make assumptions to provide BTSL parameters in cases where no data was required in SAP; for example, assumptions relating to the properties of internal walls, and thickness and layers in the building fabric, while still achieving the required heat loss and thermal mass according to the definitions of RdSAP (e.g. thermal mass only from the inner surface to a maximum of 100mm depth).

5.1.1 Simulation A results

For the ideal heating system BTSL obtains similar results to SAP, within 0.2°C and 200kWh. Such small differences between the results are expected due to the differences in assumptions and input parameters between SAP and BTSL; in particular the difference in mean external temperature (SAP external temperature is 0.7°C warmer than BTSL), and how internal walls and external walls construction materials and dimensions are specified, as discussed in Section 2.2.

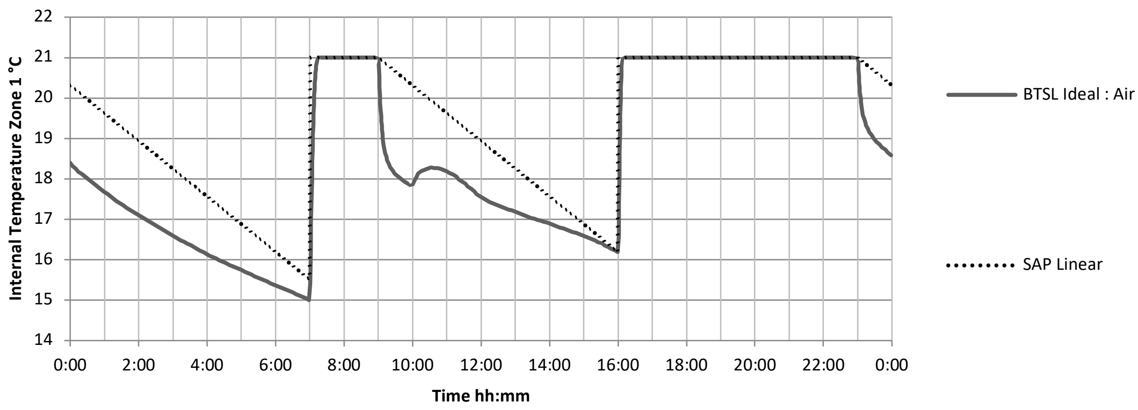


Figure 32: Z1 Internal Temperatures SAP & BTSL ideal heating cases (January)

The Figure 32 shows that BTSL ideal heating achieves a near instantaneous heating up of the building air and perfect control of the setpoint temperature, reflecting a dynamic interpretation of the SAP model assumptions. Murphy (Murphy, 2012) developed a dynamic model implementation of SAP (IDEAS) and observed a similar cool down profile to that observed here in the BTSL ideal heating case (Figure 33); similar to SAP and the BTSL ideal heating case, the physical detail of the thermal mass of radiators and heating water was not included in Murphy's study, but structure and air are separately modelled. Both the BTSL and IDEAS dynamic model exhibit a characteristic rapid air cooling after the heating period ends, followed by a slower cooling rate. This was also noted by Murphy and is attributed to the separation of thermal masses, which allow the air to cool rapidly before the stored energy in the walls creates a large enough temperature difference (between wall and air) to provide the thermal gradient to arrest the drop. Although the two dynamic models share a similarity in cooling, BTSL has a distinct increase in temperature during the daytime cooling period, which is coincident with the high solar thermal gains associated with the predominantly east facing glazing.

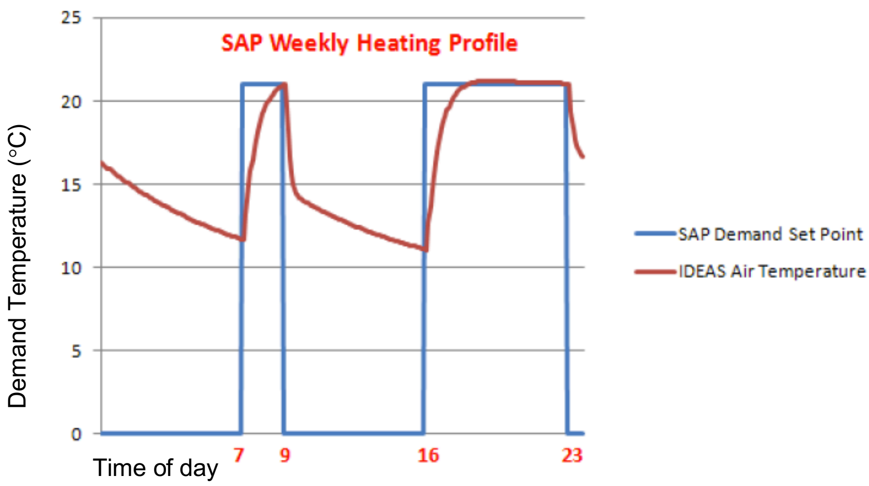


Figure 33: Dynamic 'IDEAS' model results from Murphy (Murphy, 2012)

Importantly, in this case where heating is assumed to be ideal, although the shape of the cooling curve is qualitatively different as seen in Figure 32, the temperature reached at the end of the heating off periods (0700 and 1600) match closely between dynamic and SAP estimations, and over the course of the simulation period. This suggests that the simplifications in SAP are, at least from the point of view of building fabric simulation are optimised in the right places to provide believable results.

Having verified that the ideal heating system BTSL and SAP return similar energy demand and MIT results for building and ideal heating on an annual basis, a physically realistic gas boiler heating system with thermal capacity in the boiler and radiators was introduced as described above. The results of this investigation and comparison to BTSL ideal heating case are discussed below.

5.2 Simulation B: Plant Size Ratio

Table 15: Summary of parameter space covered by simulations

Parameter	Options / Range	Notes
Plant Size Ratio	8.5 3.0 1.0 0.5	Defined as: Ratio of Boiler Rated Output/ Building Design Day Heat Loss at an external temperature of -2°C, excluding free heat gains.

The Plant Size Ratio (PSR) was varied, PSRs quoted in this section refer to the steady state ratio, whereby the heating system size was calculated using a design day temperature of -2°C, meaning the desired internal setpoint temperature can be maintained under continuous and steady state operation of the heating system. No adjustment factors have been applied to compensate for intermittency or building thermal mass. The absolute or 'accurate' PSR calculation method was discussed in section 2.3.2 and showed that more than one method exists and they rely on differing definitions of building thermal response. Therefore, it is more important here to cover a *range* of PSR which cover commonly used boiler sizes, especially pertinent for combi boilers where sizing based on space heating would not be practical and is not practised due to the mismatch of DHW and CH peak demand.

PSR was varied from a maximum of 8.5, which corresponds, in the house modelled here, to a common combi boiler output size of maximum 28kW, down to 0.5 (1.7kW Boiler Output), whereby the heating system is half the size it needs to be to maintain a steady indoor temperature when the outdoor temperature is -2°C, with no accounting for free heat gains. The BTSL combi boiler simulates a typical modulation range of a modern condensing boiler (Bosch, 2009), whereby the ratio of maximum heat output to minimum output was 5:1, meaning that the lowest available heat output of the boiler increased with PSR.

However, the practicality of choosing a boiler from a product range based on finite kW output steps will inevitably lead to oversizing of the heating system. This tendency for oversizing was noted as long ago as 1977 (Pickup and Miles, 1977b) and has been researched both in the UK by the Energy Saving Trust (Orr et al., 2009), and in Germany by Fraunhofer Institute (Wolff et al., 2004). Oversizing of heating systems is exacerbated in the case of combination appliances since the power output to provide hot water on demand often far exceeds that of the space heating, leading to little correlation between building heat load and boiler size (Orr et al., 2009). Research shows that the oversizing is prevalent and a contributing factor to heating system underperformance (Orr et al., 2009, Wolff et al., 2004) - though in principle, oversizing can lead to improved performance, because of the reduced temperature drops across oversized heat exchangers, or secondary heat exchangers, if also fitted (Pickup, 1977).

Figure 34 shows four columns for each simulated heating system scenario, representing the air temperature at the central node of each zone (Air) as well as the floor area weighted mean and the temperature used by the Room Controller (RC) for feedback. RC and air temperatures differ because the former is influenced by the temperature of the wall on which it would be fitted in order to more accurately measure the operative temperature felt by the inhabitants; in this case, the influence is modelled with a ratio of 75/25 Wall/Air temperature based on RC measurements of typical Bosch products (Bosch, 2017b), compared to the more ideal 50/50. Murphy (Murphy, 2012) noted that SAP does not specify whether operative or air temperature is controlled, and it is often assumed to be the mean air temperature; this could be classified as a type of convention error (Chapman, 1991) or definitional uncertainty ((JCGM), 2008). However, in this analysis, both temperatures have been plotted for clarity. The benchmark for comparison will be the BTSL Ideal case used in Simulation set A, chosen to avoid potential distractions regarding the different external temperature profiles and solar gains, which in SAP are monthly averages but in BTSL are necessarily variable throughout the day as well as having a small offset as described in the previous section.

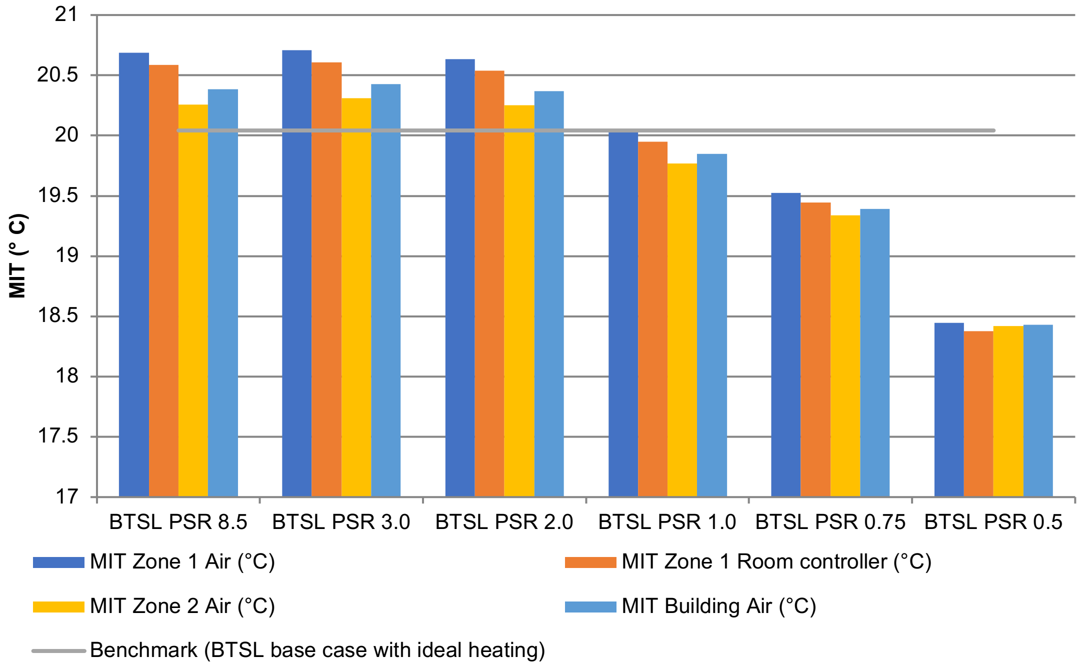


Figure 34: Mean (Oct-Apr) Internal Temperatures across PSR without 'Heat up Optimisation'.

When the 'Heat up Optimisation' is disabled in the BTSL model the heating system is restricted to operation during the programmed heating schedule. With this setup the effect of PSR is bigger. As seen in Figure 34, oversized heating systems exhibit higher MIT than the ideal case and undersized ones significantly lower. PSR of 1 predicts a MIT close to that of the ideal and SAP case, and PSR 0.75 is close to matching the heat input requirements as shown in Figure 36.

The consistently higher than benchmark temperatures, circa 0.4°C (mean MIT air), are consistent with the temperature profiles seen for those higher PSR, such as that for PSR 8.5 in Figure 35.

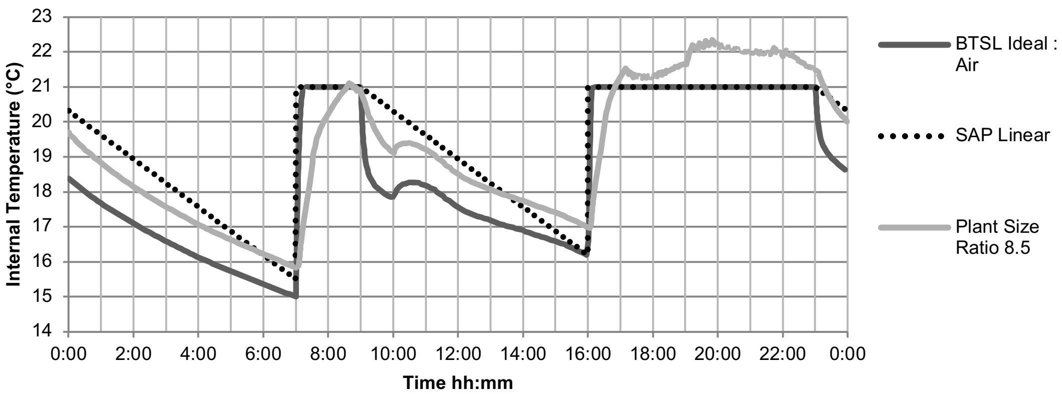


Figure 35: Internal Z1 air temperature, Ideal case, SAP and PSR 8.5 without 'Heat up optimisation'

Although the warming up curve is less rapid, as would be expected in a realistic heating system, the cooling down curve is also retarded, especially the first phase after the heating period ends. Together with the over shoot in the evening heating period, this combines to provide a consistent average overshooting of the benchmark prediction. This type of behaviour, both the retarded warm up and more gradual cool down, would seem to be consistent with the addition of the heating distribution network to the simulation (note the benchmark BTSL result had a massless ideal heating system). The heating network not only adds thermal mass but at a higher temperature than the building fabric or air. The interaction of thermal mass in the building heating system and building fabric would be a worthy path of exploration in further simulations, the heating system as a thermal store complicates the already challenging task of modelling the building fabric and how different depths of the walls should influence the indoor air temperature.

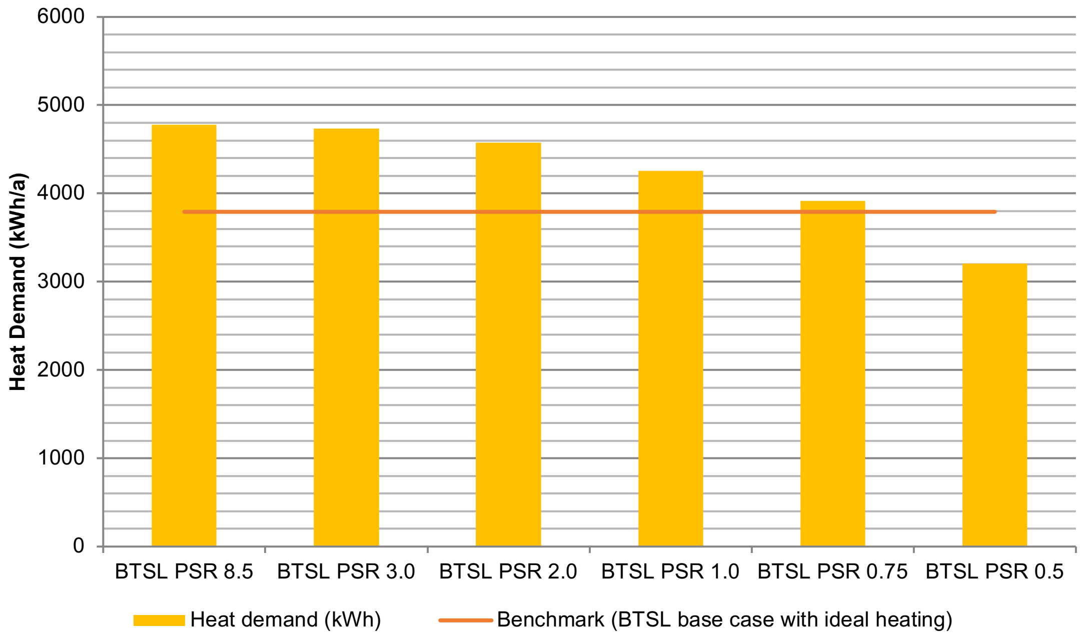


Figure 36: Heat input (Oct-Apr) requirement across PSR without 'Heat up Optimisation'. Benchmark is the BTSL base case

The smallest PSR simulated, 0.5, not only delivered lower than desired MIT but also less heat than SAP predicted, in contrast to the 0.75 PSR simulation where the internal temperature still fell short but delivered the closest amount of energy to the SAP prediction. However, a closer inspection of the internal temperatures in Figure 37 shows that a PSR of 1 (as with all PSRs) gives internal temperatures below the setpoint during the morning heating period. This failure to meet the set-point temperature consistently throughout the day occurs despite an average MIT over the heating season which matches that of the SAP and BTSL ideal prediction. During the longer evening heating period the system has enough time to reach the setpoint temperature, but with a delay of over 3 hours. This delay would probably be undesirable from the point of view of a real dwelling inhabitant, and may lead to changes in the heating program or other adaptations in order to achieve the desired internal temperatures at the right time. Such mitigating actions would all act to reduce the daily intermittency factor (effective heating schedule duration per 24 hrs) by the extension of heating periods or a transition to continuous heating with multiple setpoint temperatures (e.g. daytime / night setback).

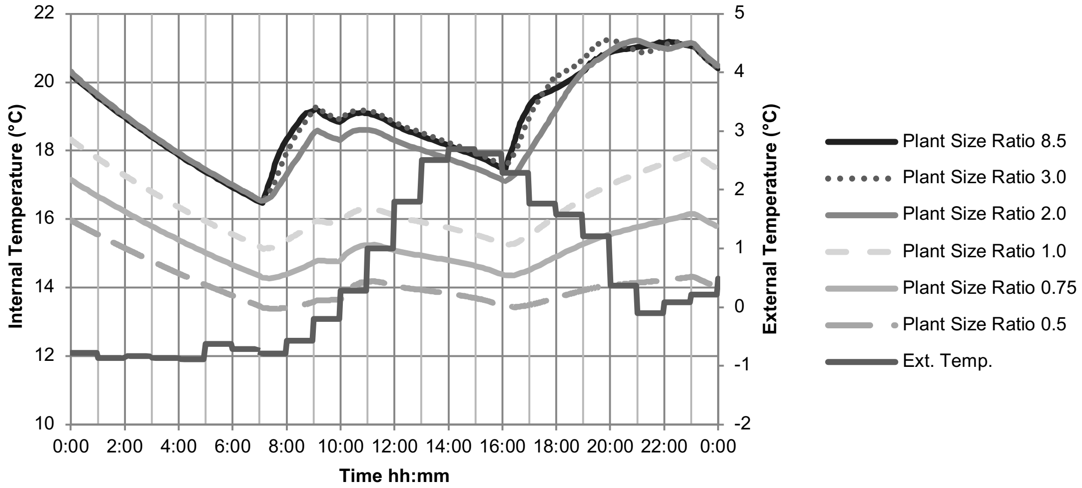


Figure 37: Z1 Internal temperatures across PSR without 'Heat up Optimisation'

Heat up optimisation (as described in section 2.3.7) in controls, is a type of heating control which determines how much earlier than the programmed time the heating needs to begin in order to deliver the desired internal temperature at the time requested. The controller must take account of the physical effects at work in the building, namely heat loss rate, thermal mass and the heat delivery rate. How exactly these algorithms work, and what weighting of input parameters, such as thermal response and optionally, outdoor temperature, is included, and how they are processed is valuable confidential intellectual property of the heating system controller developer. In the case of modelling the function in BTSL, this presents the advantage that the algorithm is close to that implemented in Bosch controllers, but disadvantageous since the details of the algorithm cannot be divulged due to confidentiality reasons.

Rerunning the PSR simulation batch with heat up optimisation functionality turned on removes the restriction that the heating cannot turn on before 0700; the controller calculates the suitable additional heating duration needed to bring the room temperature to the setpoint at 0700, according to the capabilities of the heating system itself. The internal temperature in the case of the largest simulated PSR are shown in Figure 38, the optimisation function results in 2 hours extra heating in the morning and 1 in the afternoon.

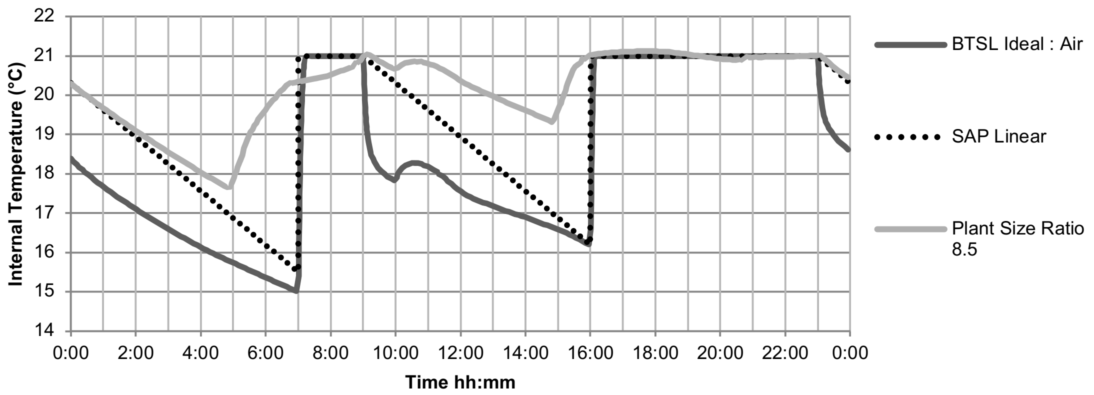


Figure 38: Z1 Internal temperatures across PSR with 'Heat up Optimisation'

While varying PSR and using the 'heat up optimisation', all dynamic BTSL cases resulted in higher MIT (**Error! Reference source not found.**) and space heating (Figure 40) than the SAP benchmark. However, the increasing trend of MIT as the PSR reduced below 2.0 was reversed for the space heating where a small decline was observed.

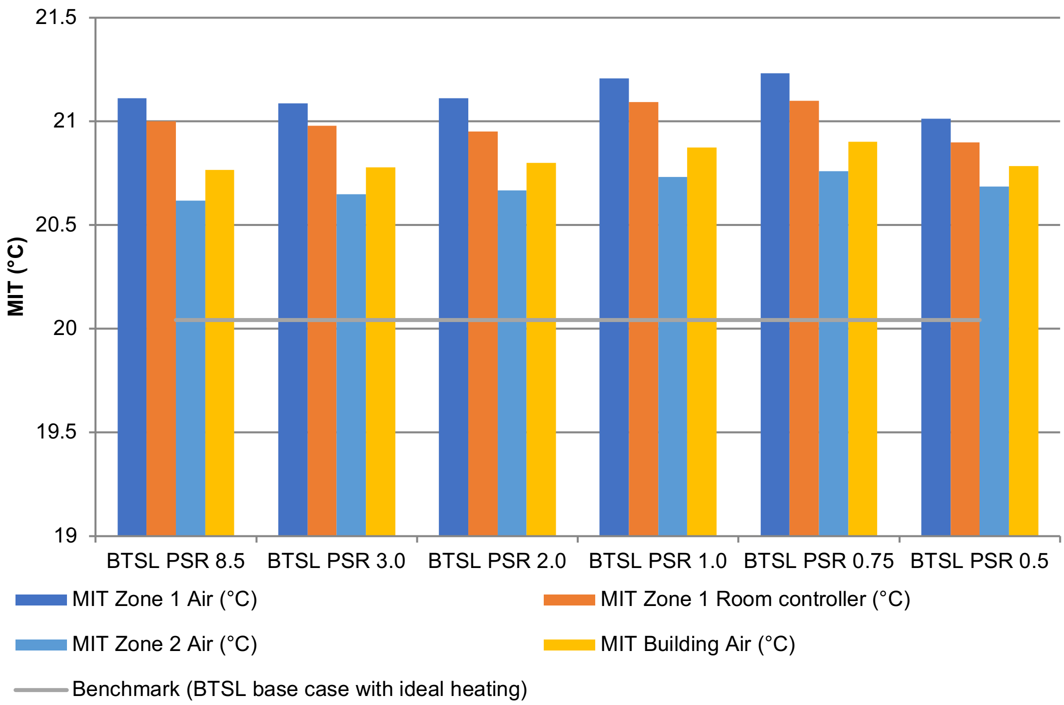


Figure 39: Mean Internal Temperatures (Oct-Apr) across PSR with 'Heat up Optimisation'.

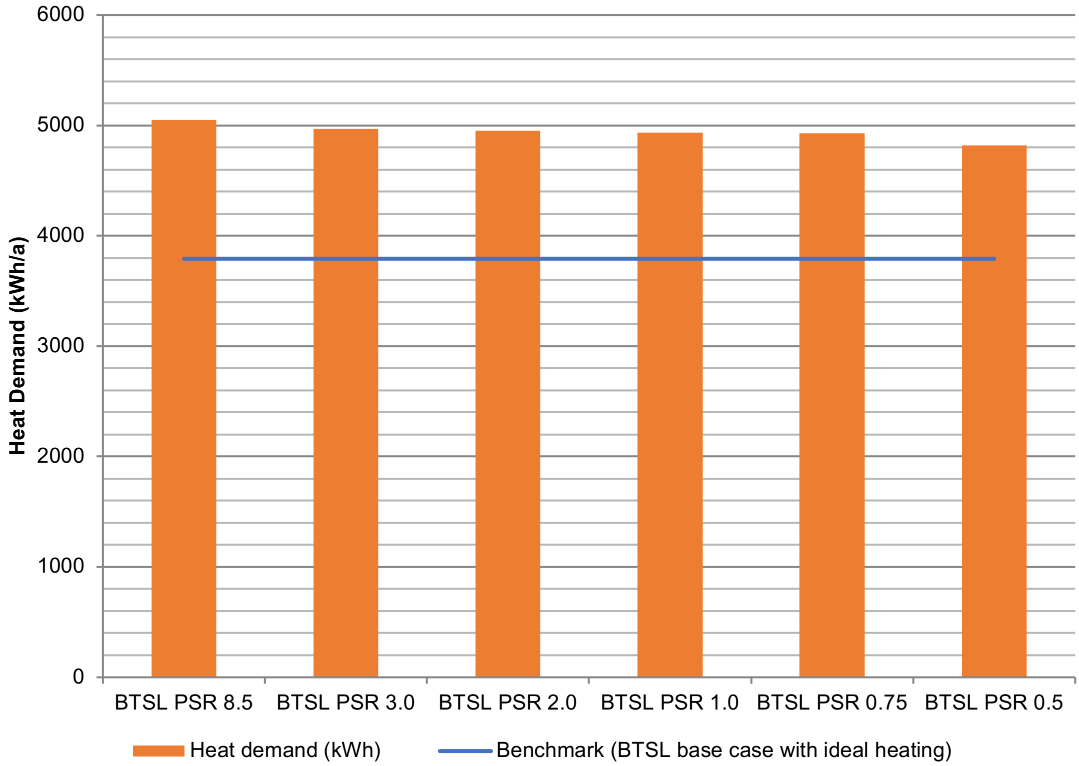


Figure 40: Heat Input Requirement (Oct- Apr) across PSR

The increasingly early starting times of the heating system can be seen in Figure 41, indicating how the MIT would gradually increase due to the longer operating times until the setpoint room temperature cannot be reached and, in the case of the PSR 0.5, even cannot arrest the temperature drop in the early morning until the outdoor temperature rises sufficiently. The predicted internal temperature profiles (Figure 41) show a PSR of 1 and 0.75 reaching the setpoint temperature in the cold month of January since the design outdoor temperature is -2°C (whereas average external temperature in the BTSL weather data is 4.6°C). However, the temperature was only reached and maintained when the heating period was over 2 hours and the previous off period was 7 hours during daytime. Only in the case of 0.5 PSR was the setpoint unable to be reached during any of the heating periods, with a corresponding drop in space heating input.

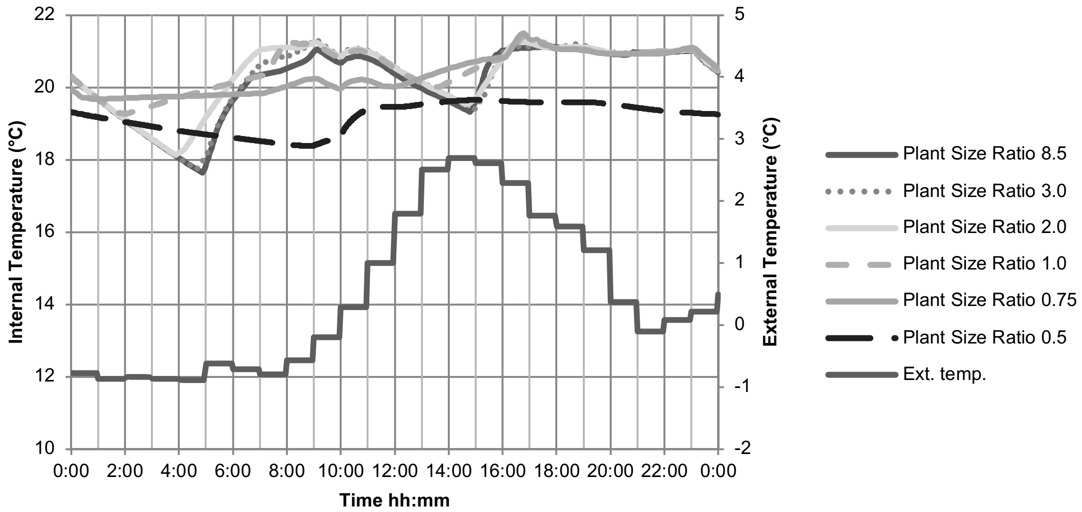


Figure 41: Z1 Internal temperatures across PSR with 'Heat up Optimisation'

Considering the cases as a whole, there is a tendency for more continuous operation with decreasing PSR. Although it may be that oversizing is a common occurrence in many buildings with gas boiler central heating systems (a topic which is discussed later in this thesis in more detail), the implications for the uptake of heating systems which, for cost or technical reasons, do not lend themselves to oversizing (see also Section 2.3.4) means that changes to heating profiles will be likely in an attempt to attain the same comfort levels at the same times as with an oversized boiler.

Due to the level of detail in BTSL, it is possible to take a look deeper into the simulated behaviour of the virtual heating system, in particular the heating power delivered at any given time. As mentioned in section 2.6.2.1, SAP itself makes an adjustment to the efficiency values measured and recorded in the PCDB based on field measurements showing lower than reported efficiencies in real world use (Orr et al., 2009). No direct connection regarding the modulation level and PSR of the heating device is given (BRE, 2016), rather a standard reduction of efficiency is implemented. As discussed in section 2.3.3 the influencing parameters on boiler efficiency are complex and an amalgamation based on field measurements is a pragmatic way to approach the problem. But detailed dynamic modelling gives the opportunity to go under the cover of the boiler and analyse virtual measurements. Therefore, a closer look at the heating device behaviour is warranted, which can be further analysed in the field data later in the thesis.

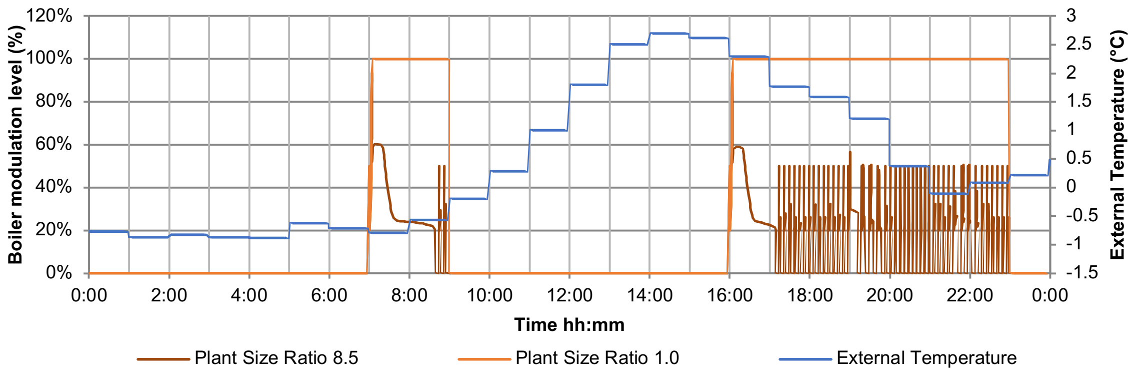


Figure 42: Boiler power modulation level on January day across 2 PSR levels (Heat demand 0700-0900 & 1600-2300, PSR 1 at 100%, PSR 8.5 starts at 60% before modulating down and cycling until end of period)

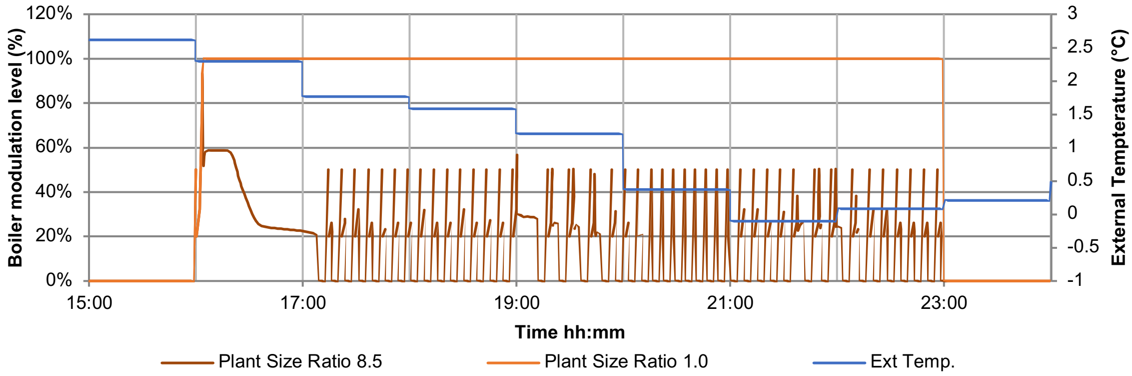


Figure 43: January day afternoon boiler power behaviour across 2 PSR levels (Heat demand 1600-2300, PSR 1 at 100%, PSR 8.5 starts at 60% before modulating down and cycling until end of period)

In Figure 42 a significant dynamic variation in boiler behaviour can be seen in the sense of the boiler output with time on the same January day as plotted in Figure 37. As the outside temperature reaches the design temperature then a boiler of PSR 1 is expected to work at roughly maximum output to maintain the desired internal temperature depending on gains and change in external temperature. However, the ideal plant size calculation generally takes little consideration of the bi modal heating schedule practised in most UK households, therefore despite the full power operation shown the internal temperature is not reached (as shown in earlier in Figure 37). The case with an oversized boiler such as that with a PSR of 8.5 is that the initial almost full power operation is modulated down with time before necessitating a shutting down of the boiler after approximately 1.5 hours. This behaviour is repeated not only in the morning heating period, but also in the afternoon, in both cases, despite the internal temperature also not being reached. The longer afternoon period shown in Figure 43 shows more clearly that the boiler in the PSR8.5 case, i.e. oversized to a level where minimum modulation it too high to prevent premature termination of the boiler, modulates down the thermal power output to the minimum level set in the boiler controller, in this case 20%, before having to switch off. Termination of boiler operation is triggered when, due to the over delivery of heat, the central heating water temperature rises above the boiler internally measured setpoint, normally the flow temperature exiting the boiler. This is the result of the low temperature drop across the heating system. The extent to which the boiler consistently cycles on and off around its lower modulation limit is shown to be dependent on the PSR for a given controller type, as seen in Figure 44. However, this should be seen against the backdrop of the level of temperature control in the building, more on which in the following section.

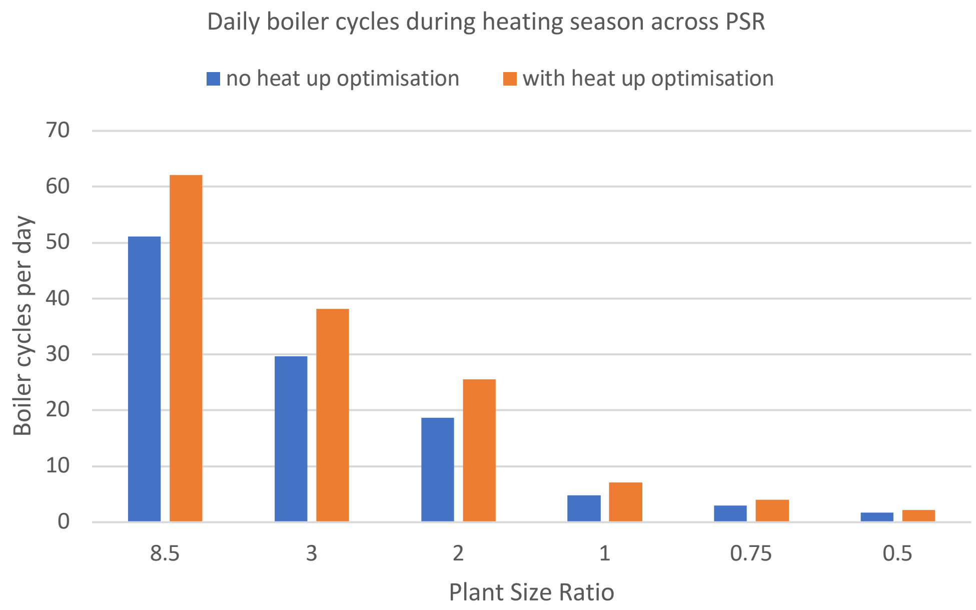


Figure 44: Number of boiler ON/OFF cycles per day for heating according to PSR

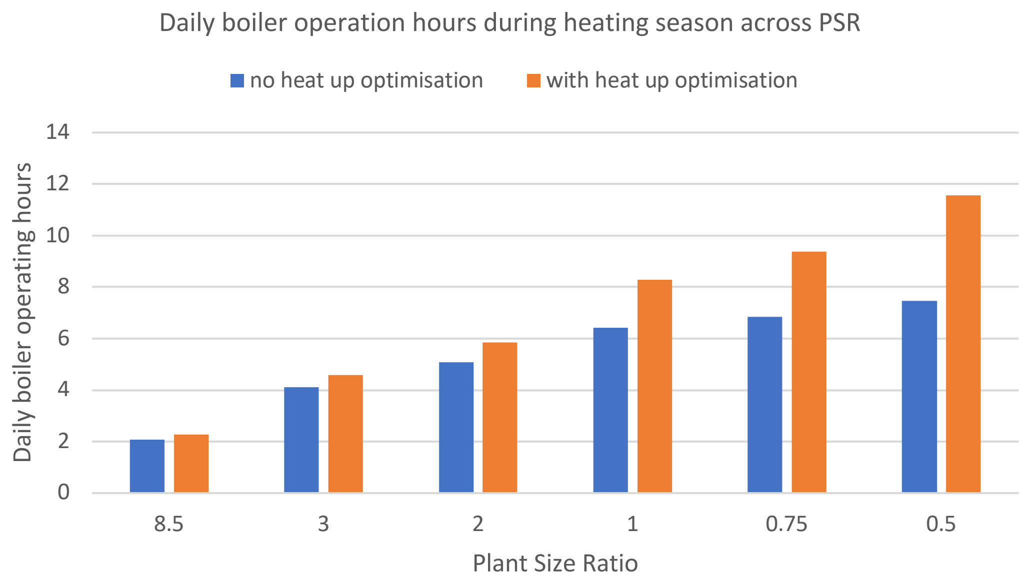


Figure 45: Boiler operating hours, per day, for heating according to PSR

Boiler cycling behaviour as summarised in Figure 44 also impacts the running time of the boiler as shown in Figure 45. In order to achieve similar heat input levels for PSR

8.5-2, but with the respective larger boiler power levels, then the operating hours are correspondingly lower. For the case of fixed heating schedule, without heat up optimisation, then the limit is reached for the smaller, undersized boilers corresponding to PSRs less than 1. However, with heat up optimisation, this enforced intermittency restriction is removed and the smaller boilers are able, and required to, operate for longer periods, more closely approximating constant operation.

Efficiency of the boiler, as calculated by BTSL (gas consumed/heat delivered) in Figure 46, shows a trend which implies that longer running times are beneficial for efficiency with an almost 10% increase between PSR 8.5 and 0.5, but as we have seen, this was at the expense of an ability to reach the required internal temperature and therefore occupancy comfort. Heat up optimisation has only a marginal improvement effect on the efficiency for any given PSR, but looking at this in the context of MIT, then it would seem that on a purely annual averaged basis, the PSR of 0.5 might seem a logical choice (if it were not for the thermal comfort penalty that becomes visible on the hour or minute scale).

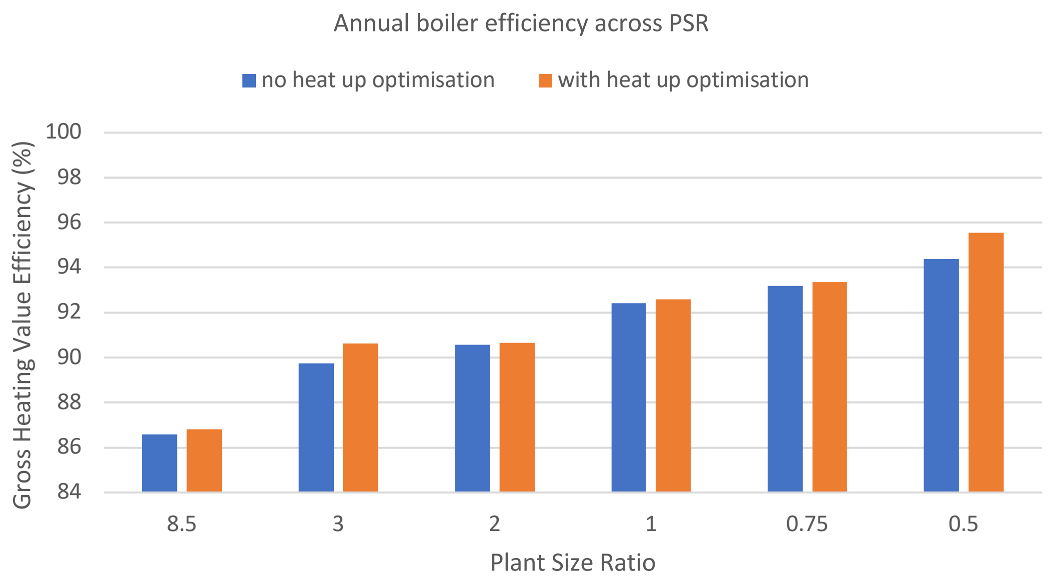


Figure 46: Boiler annual efficiency using net heating value, across PSR

A heating system should deliver a balance of both comfort and efficiency. The trade-off between these two goals can be investigated further by looking at the relationship of delivered heat with both MIT and intermittency (ratio of boiler running hours per 24hrs). In Figure 47 and Figure 48 the previous data has been replotted to allow for this analysis.

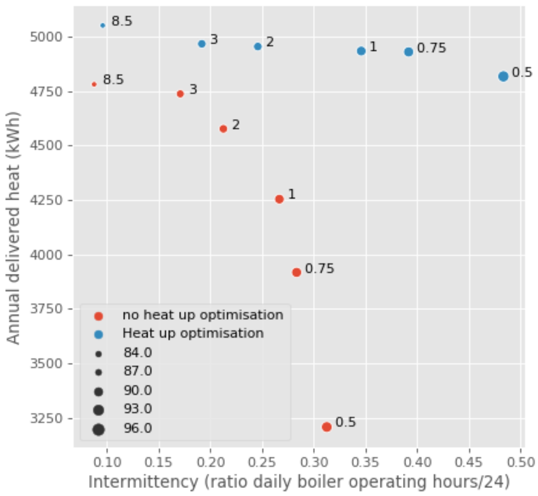


Figure 47: Boiler intermittency against delivered heat (Oct-Apr), size of data points according to efficiency, colour for heat up optimisation active, data labels for PSR

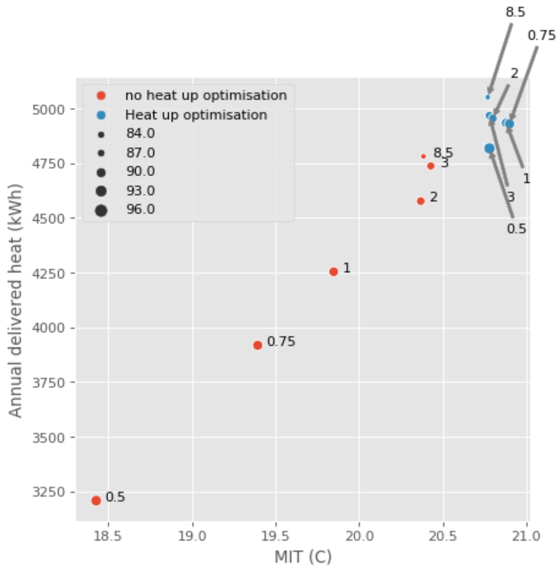


Figure 48: MIT against delivered heat (Oct-Apr), size of data points according to efficiency, colour for heat up optimisation active

With the boiler operating time limited by the heating schedule the decrease in PSR quickly leads to a greatly reduced heat delivery and corresponding MIT, the solitary gain to be made is an increased efficiency. Heat up optimisation allows for, on the annual level, a preservation of the MIT with modest decrease in delivered heat and therefore efficiency. In the case of heat up optimisation and weather compensation it is clear that they result in the longer runtimes and higher temperature. The question has been whether there is an energy demand penalty to be paid for heating outside the traditional schedule/occupancy periods. This evidence would suggest that lower PSR coupled with longer runtimes, driven by heat up optimisation, would not result in higher energy demand and would preserve the overall mean internal temperature.

With a PSR of 1 the energy input and reaction of the temperature is as expected but the delivered energy is not enough to raise in the internal temperature to the desired level within the time given, even though the classic PSR calculation may give this impression (see Section 2.3.2), the dynamics of the heating/building system prevent it. With larger PSRs, one could reasonably expect the lag caused by the thermal mass of the building to be overcome with a higher rate of thermal energy delivered, the thermal capacity of the building, as represented by the thermal mass, is able to be ‘charged’ faster when larger PSR heating systems inject the necessary heating power. This is a phenomenon integrated into the CIBSE heating system specification calculation, which divides buildings into high and low thermal mass categories (see Table 1 (CIBSE, 2015)). To a certain extent this variation of internal temperature with PSR seems to be present, but still after the initial warming of the internal air the boiler then enters a period of on/off cycling, the reasons for which are not apparent from the figures presented hereto.

The design stage PSR adjustment factors normally take the heating ON/OFF hours or ratio thereof as an input to calculate an appropriate oversizing factor (section 2.3.2) (CIBSE, 2015). This may suffice if the ON/OFF periods are present as 2 homogenous blocks (1 ON and 1 OFF) in a 24-hour period, but seem less applicable in the case of the commonly recorded heating schedule of UK occupant, namely ON in the morning and ON in the evening. The 28kW boiler simulated fails to meet the internal temperature setpoint during the morning heating period despite representing a PSR that would not be recommended in the standard calculation methods, implying that no amount of sensible oversizing could be implemented to meet comfort requirements without resorting to heat up optimisation algorithms or manual intervention in the form of a reprogrammed schedule. The issue of plant size adaptation for intermittency seems more complex than one simple equation or rule of thumb, and the recommendation for dynamic simulation from CIBSE is in principle sensible, but whether this is applicable for common residential heating installations remains to be seen. It could be that since the heating schedules are so common among the UK housing stock (Huebner et al., 2013a) for a given heating schedule that standardised adjustment factors for plant size could be implemented in the design phase. Also, during Energy Performance Certificate assessments with SAP, adjustments to mean internal temperatures and efficiency could be determined based on PSR and control types for existing systems.

Variation in boiler power output and PSR for a heating installation in a given house and heating schedule has been shown in these simulations, to affect the ability of the system to effectively control internal temperature, in particular, with regards to comfort in the temporal domain. Efficiency suffers and rates of cycling of the boiler also increase with larger PSRs, two causally linked issues which are both detrimental to the boiler's performance and lifetime. Since, for the majority of buildings, combi boilers are already installed and they, like those sized for new build, are chosen on the basis of DHW demand, then there is a strong case to believe that many boilers would be oversized (further analysis into this assumption to come later in the thesis). Besides replacing the boiler for a smaller boiler, either a combi which would impact hot water comfort or redesigning the system to one with hot water storage, alternative mitigation strategies for the impact of oversized boilers may be worth investigating, especially those with low cost and disruption. In this section, all heating systems were simulated with a flow temperature modulating controller, both with and without heat up optimisation. Taking a look at alternative control strategies would offer a less drastic heating system intervention than boiler replacement to counter the issues associated with oversizing.

5.3 Simulation C: Heating System Control

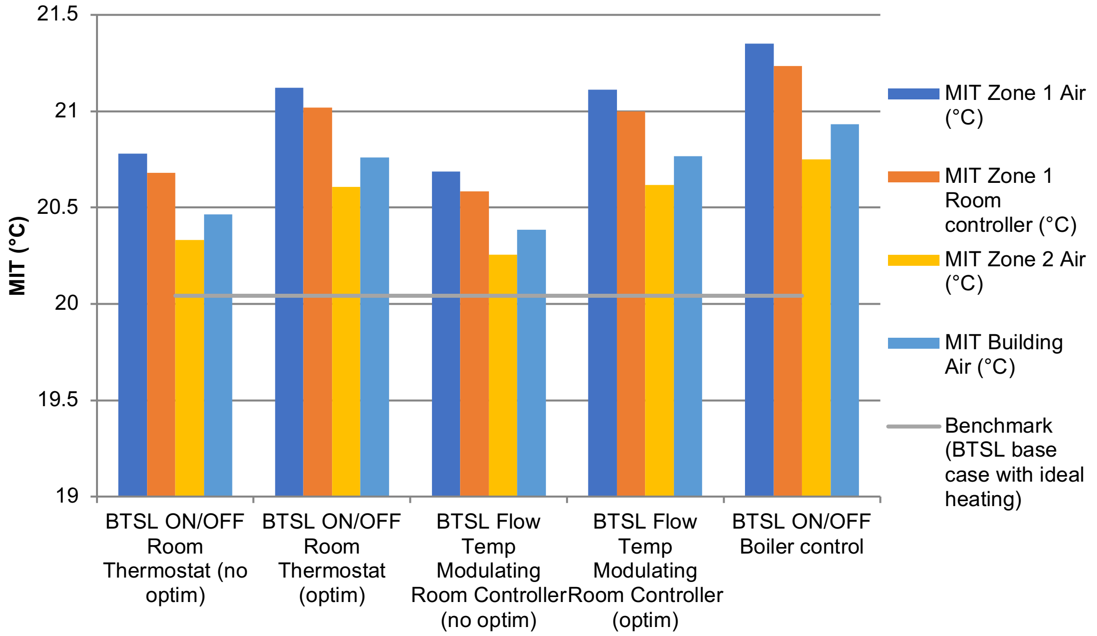
In this set of simulations, the building is again kept constant (as per Simulation set A and B) as is the heating schedule, as per SAP. The chosen boiler size is a 28kW combi (same as used for the PSR 8.5 simulations in the previous chapter) as this represents a typically sized combi boiler in the UK and the hot water capacity is suitable for this size of property (100m^2, 2-3 occupants, max 10l/min at 40K temperature rise of DHW).

The following simulations seek to compare two common controller types, including the basic required by Building Regulations, and the next level of sophistication which does not require significant hardware additions such as outdoor temperature sensors. As mentioned, there is a minimum control standard stipulated in UK legislation, but the reality in the UK's heating systems is that installed controls remain basic, with many houses falling below the standards (HHWT, 2010b), so more advanced controls have not been simulated since the existing housing stock is starting from a low level. But a basic boiler timer was also simulated due to the anecdotal evidence that many of such systems are still operational.

Zonal controls (Beizaee et al., 2015), model predictive control (Bosschaerts et al., 2017, Prívara et al., 2011), variations thereof and numerous other novel control methods have been researched both in simulation and in practice. The research carried out and described here does not look to repeat or provide an exhaustive analysis of control methodology, but does seek to compare common control types to understand the relative improvements to internal temperature and heat demand that can be offered by modest changes to the control system in light of the impact of plant size on system dynamics.

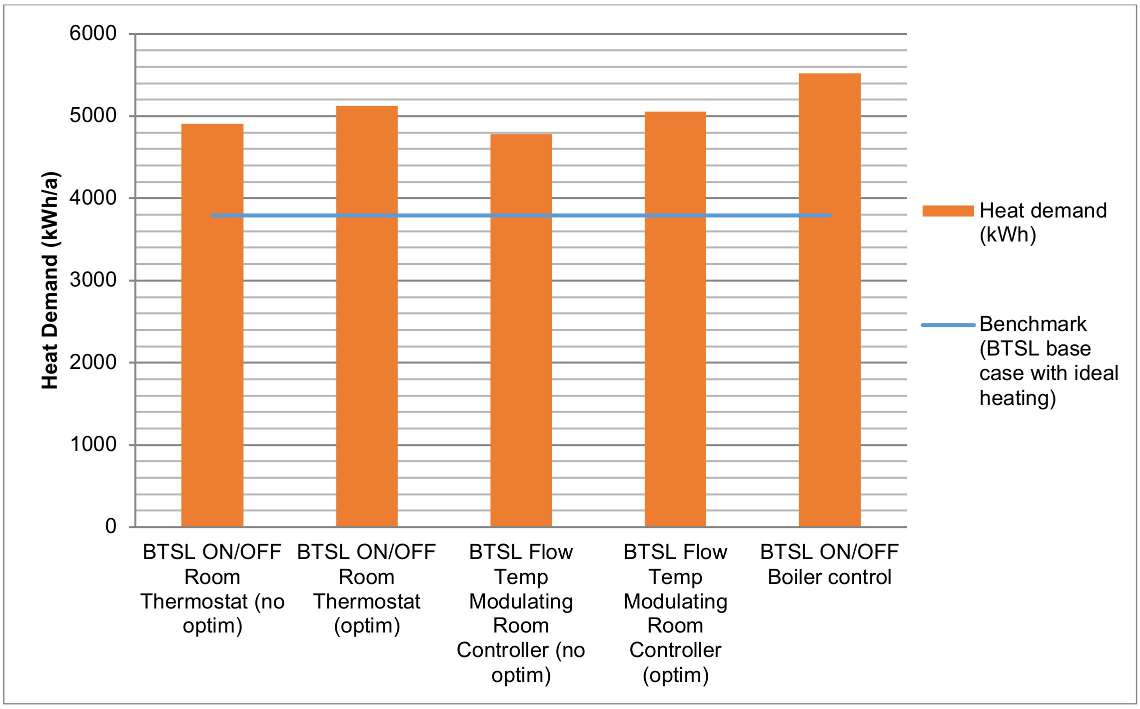
Table 16: Summary of parameter space covered by simulations

Parameter	Options / Range	Notes
Heating Controls	• Boiler timer • ON/OFF room controller • Flow temperature modulating room controller	SAP time schedule for all variants Sub-option: heat up optimisation



TRV	X	X	X	X	X
Room Controller Type	ON/OFF	ON/OFF	Modulating	Modulating	-
Heat Up Optimisation	-	X	-	X	X

Figure 49: Mean (Oct-Apr) Internal Temperatures across Heating Control Type (with and without heat up optimization). Benchmark is the BTSL base case (i.e. instantaneous no thermal mass heating).



TRV	X	X	X	X	X
Room Controller Type	ON/OFF	ON/OFF	Modulating	Modulating	-
Heat up Optimisation	-	X	-	X	-

Figure 50: Heat Input Requirement (Oct-Apr) across Heating Control Type. Base Case BTSL result.

Figure 49 and Figure 50 show that all BTSL model results simulating heating systems with thermal mass result in higher MIT and space heating energy demand than predicted by SAP (as was seen in the previous section for PSR 8.5). It should be reminded that SAP utilises a 0.7°C higher external temperature than the BSTL model, which is expected to raise MIT and reduce energy demand in the former model. The variation within the BTSL simulations shows up to 0.5°C and 300kWh/a variation. The two BTSL calculations with the lowest MIT and space heating requirement are the cases without heat up optimisation (which aims to achieve setpoint temperature by the start of the programmer period); the modulating thermostat shows the lower result.

The internal temperature plots shown in Figure 51 and Figure 52 represent the Zone 1 conditions across a day in early January and allow closer investigation of the dynamic effects. These figures illustrate the temperature overshoot of a simple ON/OFF control compared to control which modulates the flow temperature of the space heating water. All simulations from the BTSL model, including the physically realistic heating system, exhibit a slower internal temperature decay than that derived in the absence of this heating system. With a physically realistic heating system, the property therefore has a higher room temperature at the start of each heating period. Given that the building fabric remains the same throughout all the simulations, the addition of the heating system, with its associated thermal storage, is likely to be responsible for this slower temperature decay, through the delivery of residual heat at the end of the heating period. Air temperature in Figure 51 and Figure 52 is consistently higher than the RC (wall influenced) temperature during the heating period but during cooling the difference in thermal mass can be seen as the RC (and therefore the wall) temperature cools more slowly and crosses the air temperature. This is to be expected because RC contains a proportion of wall temperature, which is lower than air temperature. An additional feature of note is the increase in internal temperature shown in all situations between 1000 and 1100, this is directly related to the solar gain and the east facing orientation of the majority of the windows.

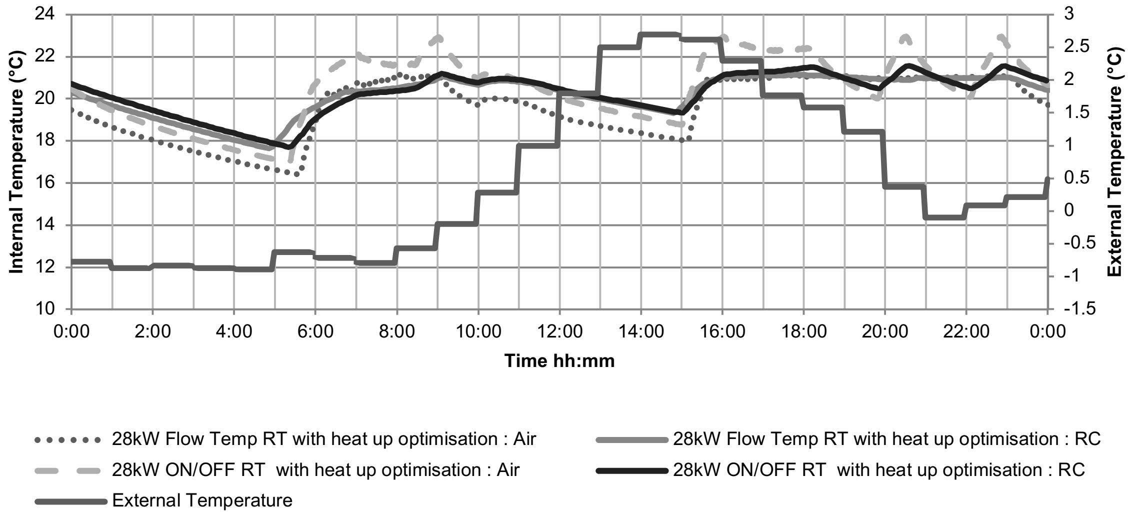


Figure 51: Z1 Internal Temperatures across Heating Control Types with ‘Heat up Optimisation’ (January)

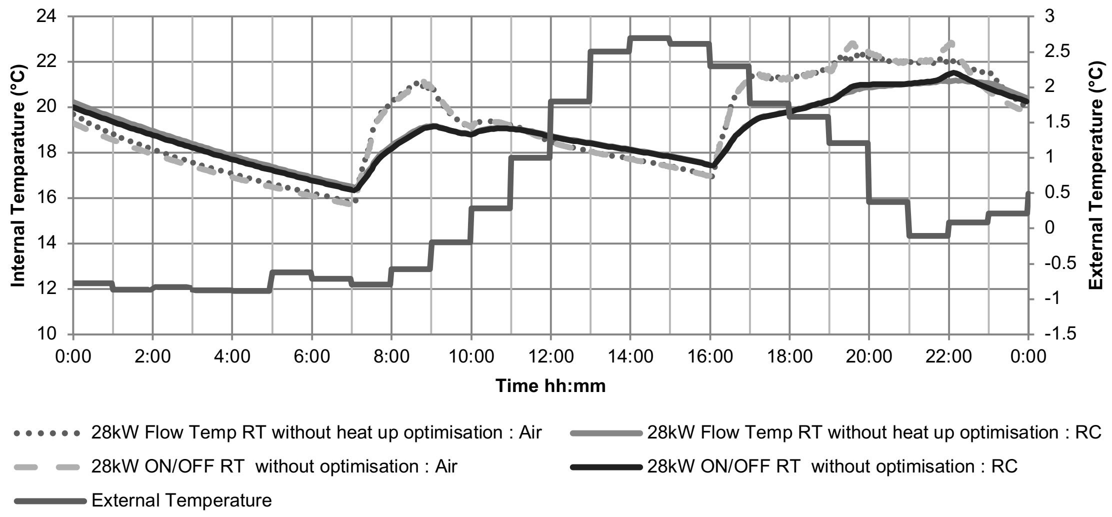


Figure 52: Z1 Internal Temperatures across Heating Control Types without ‘Heat up Optimisation’ (January)

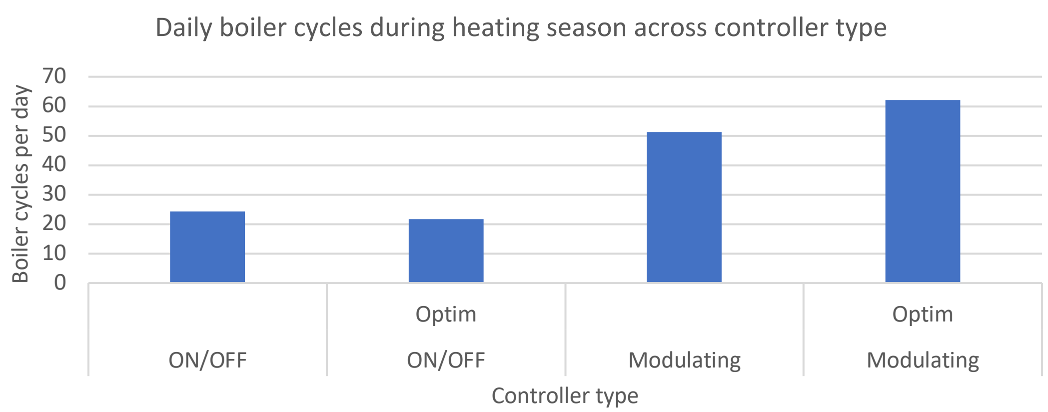


Figure 53: Boiler cycles per day categorised by controller type

Interestingly, when the control system is changed there is a dramatic difference in cycling behaviour with ON/OFF exhibiting less cycles, for example the average CH cycles per day for a PSR 8.5 sized boiler with the simple ON/OFF room controller is a mere 21.6 cycles per day, lower than that observed with a modulating control. This is not what might be expected considering that the modulating control is considered more advanced and is part of the higher class of controls according to the standards. This may be due to the operating goal of the modulating control compared to simple ON/OFF. A modulating control aims to match the thermal output of the boiler to the current building load, as best as possible, if the boiler is not capable of providing that low level of power then the control may simply continue to call for this undeliverable low level, resulting in increased cycling. The ON/OFF control will aim to maintain the internally measured flow temperature and may be allowing longer between cycles for the temperature to drop before re starting the boiler as a way of compensating for the unknown building load. However, this difference in cycling is not seen in a significant difference in operating hours.

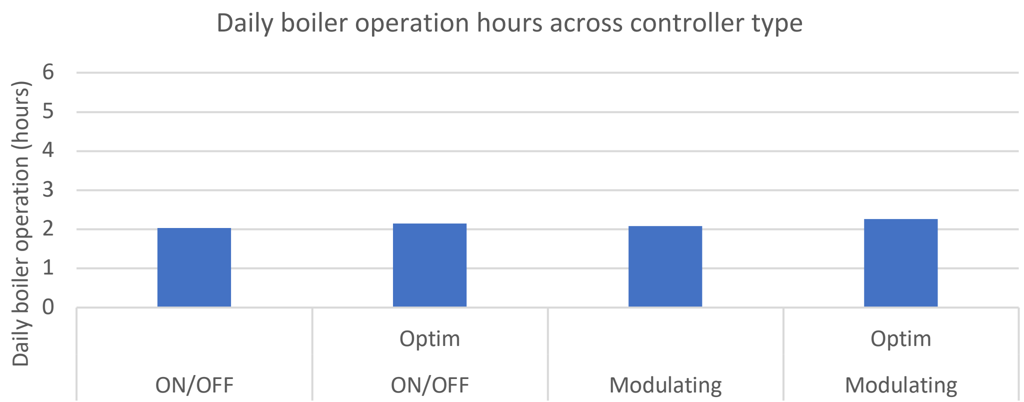


Figure 54: Boiler space heating operation hours per day categorised by controller

Boiler efficiency remained lower than expected, and lower than the boiler rating, throughout the simulations, achieving the same level reached by the original PSR8.5 simulation, varying from 86.8% for modulating control with optimisation down to 85.9% for the ON/OFF room thermostat.

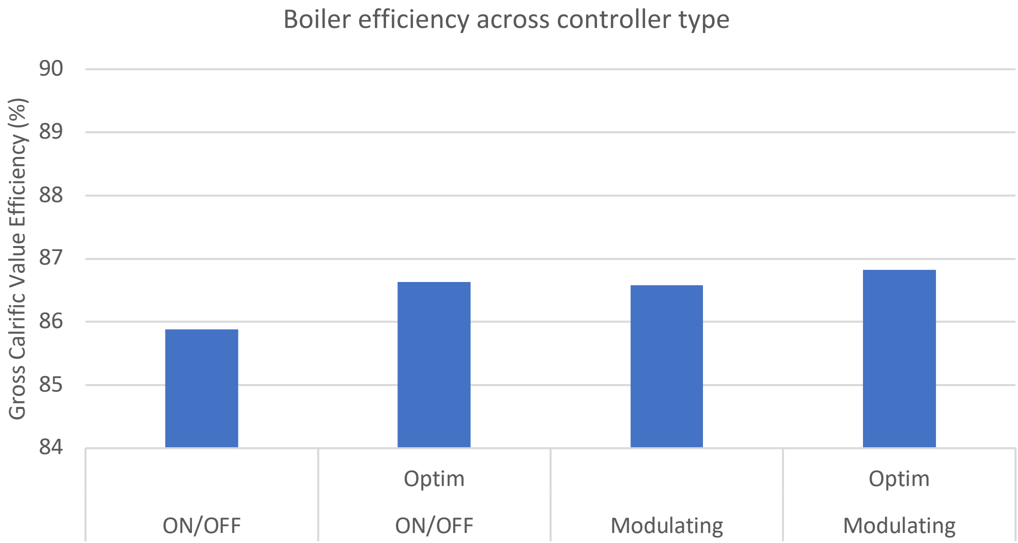


Figure 55: Boiler GCV efficiency categorised by controller

Although the limited range of control types simulated shows that internal temperatures and energy demand are both affected by the control selection, the effects are smaller than those seen with PSR variation. Research has indicated that improvements to controls, such as zonal systems (Beizaee et al., 2015), can improve system performance through better and more targeted control algorithms. The evidence here does not contradict those findings, but greater improvements may be possible by looking at the fundamentals of the heating system such as PSR and heating circuit hydraulic properties. In a sense, this reinforces the concept that good software cannot always help to improve bad hardware.

5.4 Simulation D: House, thermal mass & heat loss

For the purpose of this section of the analysis, four additional houses were simulated with one of the heating system variants from the Simulation C results. By varying the building characteristics, it can be assessed if the trends seen so far are consistent in other types of houses, or whether they are manifested in different ways. The same SAP user profile (set point temperatures/timing and constant internal gains) was utilised to ensure the same level of consistency with SAP methodology. The SAP user block calculated internal gains as per SAP, on the basis of floor area per month, and maintains them at a constant level throughout the relevant month. Solar gain is calculated in line with TRNSYS and BTSL methods. Again, no additional ventilation or DHW schedule was implemented. The heating system was maintained as a constant throughout all the simulations in this section and was chosen as:

- 28kW Boiler
- ON/OFF Room Thermostat
- 80/60°C (Flow/Return) Radiator System with TRVs

According to the English Housing Survey (DCLG, 2017), a significant proportion of the owner occupied and rented English housing stock is terraced (20%) and in the range 70-89m^2 (30%), whereas the previously simulated house was a 100m^2 detached building.

Therefore, from the archetypes in the BTSL library, two terraced houses were chosen as a contrast that will be broadly indicative of a large proportion of the stock, each of which has a pre and post theoretical renovation thermal performance. The virtual buildings selected, and their shorthand abbreviations, are summarised below:

Table 17: Building variants, naming and explanation

Building Abbr.	House Type	Renovated	Representative Country
RMHB-DE	Mid Terrace	NO	Germany
RMHN-DE	Mid Terrace	YES	Germany
RMHB-GB	Mid Terrace	NO	UK
RMHN-GB	Mid Terrace	YES	UK

The buildings will be referred to by their abbreviations for the remainder of this section and thesis. As further explanation, the abbreviations come from German origins but can be roughly interpreted as follows; RMH, refers to Row Middle House and B/N denote Basic[11] (pre-renovation, typical housing stock) and New (post renovation). DE and GB are for German and UK variants. It is not the case that all 'B' houses have consistent thermal performance to each other, as demonstrated by RMHB-DE having a higher-level insulation than RMHB-GB. A full summary of the headline thermal performance characteristics of the virtual buildings are in the table below (Heat loss on a design day of 21°C internal temperature and -2°C outdoor temperature).

Table 18: Summary of virtual building characteristics

Building	Total Floor Area (m²)	Relative Heat Load (W/m²)	Total Heat Load (kW)	Heat Loss by Transm. (kW)	Heat Loss by Ventil. (kW)	Total Thermal Capacity (kJ/K)	Total Volume (m³)	Window Area (m²)
RMHB_DE	98.00	67.39	6.60	5.68	0.93	346.23	230.82	24.12
RMHN_DE	98.00	21.77	2.13	1.58	0.56	359.26	239.51	26.51
RMHB_GB	88.16	90.28	7.96	5.64	2.32	315.81	210.54	15.26
RMHN_GB	88.16	58.39	5.15	2.80	2.35	320.16	213.44	15.29

[11] 'B' originally stood for 'Bestand' in the BTSL software library, which contained a mixture of German and English acronyms and descriptions. English equivalents, but not always literally accurate translations have been used here for the reader's convenience

Heat loss has been broken down into the ventilation and fabric losses, which are plotted in the following figure, with the total building fabric thermal capacity. The thermal capacity shown is a simple summing of all building elements and therefore differentiates itself from the TMP (Thermal Mass Parameter) in SAP by not limiting the depth to which the thermal mass is deemed relevant (which is taken care of in the TRNSYS simulation). The building model used in simulation sections 5.1-5.3 (Simulations A-C) is shown also as reference.

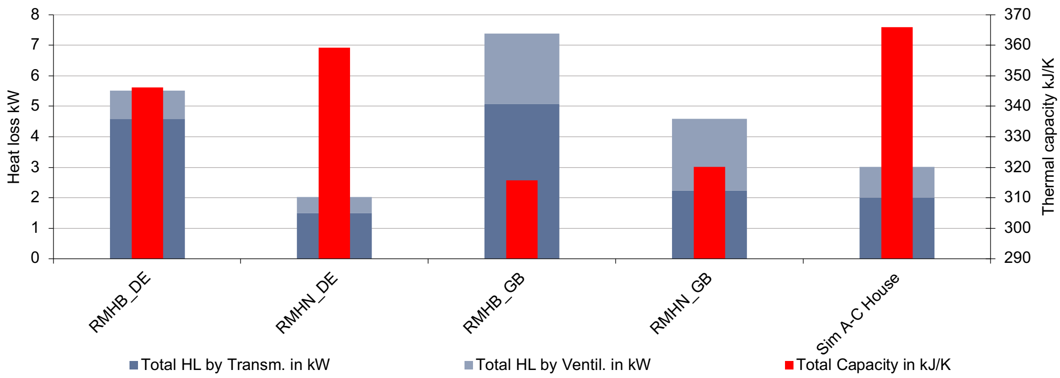


Figure 56: Virtual house Heat loss breakdown (fabric transmission & ventilation) and total thermal capacity

SAP characteristics of the buildings such as Heat Loss Parameter and Thermal Mass parameter are per unit of floor area and, in the case of thermal mass, considers the layers of the building fabric closest to the internal living space which are more influential in the internal temperature damping. Considering the totals of heat loss and thermal capacity (without the boundary layer requirement of SAP), three of the houses to be simulated in this section have higher heat losses and lower thermal capacity than that on the previous sections. Only RMHN-DE has a similar 'low heat loss, high thermal capacity' characteristic as the house simulated in sections 5.1-5.3 (Simulations A-C). The houses to be simulated in this section represent a spread of heat loss, between the older 'B' variants compared to the new 'N' versions. The new German house has reduced heat loss and increased thermal mass to adhere to the experience of Bosch simulation colleagues that the German building regulations favour more thermally massive construction methods. The UK house thermal mass remains almost unchanged.

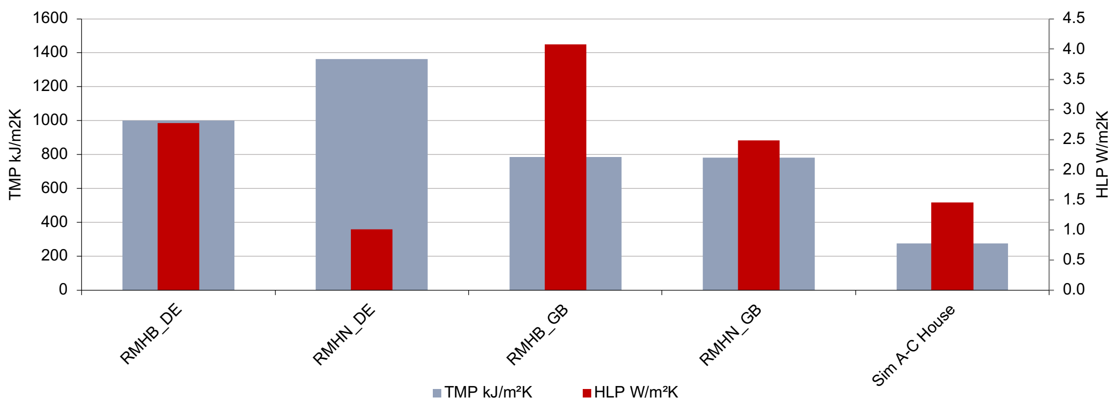


Figure 57: SAP parameters (TMP and HLC) for virtual simulation houses

For each house, a simulation was performed for a 'typical' boiler of 28kW and one with a tailored PSR=1 boiler, intermediate plant size ratios and undersized (PSR<1) were not simulated as in Simulation B. In the case of RMHN-DE, the determination of the boiler size corresponding to PSR1 was done, as was the case with the other houses, on the basis of an Excel spreadsheet calculation. The Excel spreadsheet is part of the BTSL documentation and serves two purposes. First and foremost, the spreadsheet contains the input data used by BTSL to create the TRNSYS building model to be used in the simulation, the data is read into MATLAB Simulink from the '.xls' file and parsed into the correct format. Secondarily, the spreadsheet is used as an easy access means of interrogating the building data, creating new houses and for the calculation of visualisation of secondary parameters. The heat loss and thermal mass parameters in Figure 56 and Figure 57 are two such examples. Therefore, there is a possibility of these secondary calculated parameters, which exist only in the spreadsheet calculations, to be different to the way TRNSYS and BTSL models the building based on the raw input data. In the case of RMHN_DE just such a discrepancy arose, which highlights an issue that can afflict a building physics assessment where two methods are used. In the setup of the simulations, the boiler size was chosen on the basis of the Excel based building heat loss calculation, with the aim of using a fixed 28kW boiler and a boiler fitting for the design day heat load for a PSR of 1. In the case of RMHN_DE, it was seen after the simulations that the building heat loss (as seen in the PTG charts later in this chapter) was only a third of what was expected. After reviewing the Excel spreadsheet, it was found that the total building heat loss used to calculate and select the PSR1 suitable boiler was in fact based on a sum of zones 1-4, assuming that zone 5 (attic/loft) was effectively the outdoor space but that the roof was highly insulated rather than the attic/loft interface. This assumption did not match the results of the BTSL dynamic simulation, therefore the heat loss figures were corrected to consider the full building fabric. But the simulations were not rerun for RMHN_DE therefore the PSR 1 became a PSR of 2.3. Further explanation of how the PTG was used to make this observation is presented later in this chapter together with the PTG calculations.

The simulations were run and summarised into monthly energy demand and power levels to analyse the results from the different houses. Whereas for simulation sets in the previous sections the house remained constant, here the different floor area of the German and British houses means that the implementation of the SAP method for internal gains, excluding solar, results in a higher monthly internal gain for the German house in line with the larger floor area. Since the floor area did not change between ‘B’ and ‘N’ variants, only the former is plotted in the chart below.

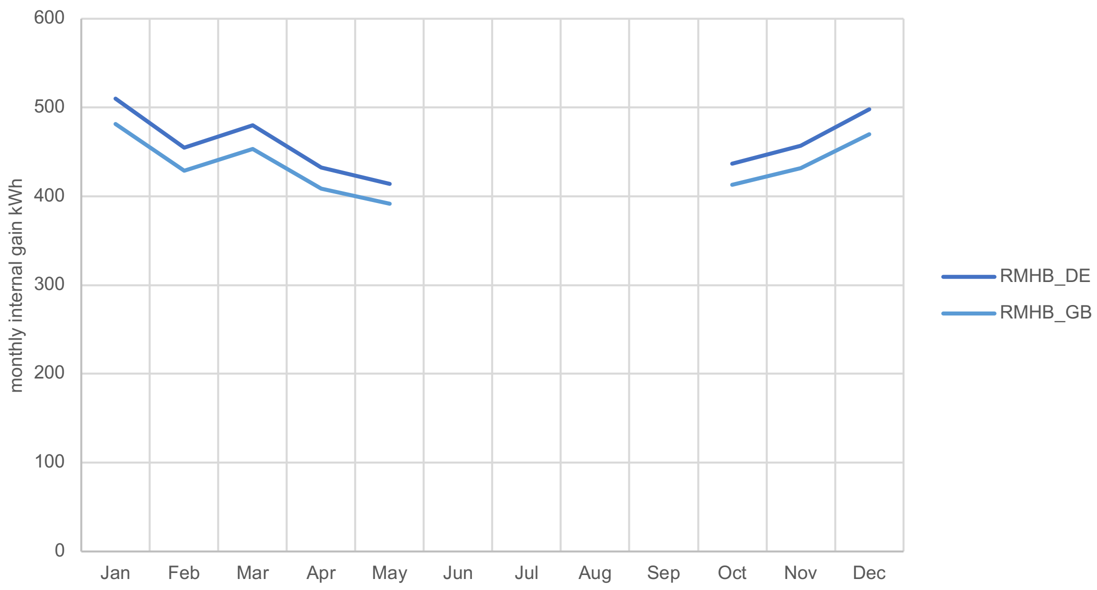


Figure 58: Monthly internal gains (excluding solar) for DE and GB houses during heating period

Solar gains, as per the previous BTSL simulations, are calculated on a dynamic basis using the solar irradiation and building/glazing properties. The dynamic calculation method drives the deviation from the SAP methodology and also the variation between all of the houses simulated here, since the glazing types vary between the old and new building types and the window areas are different between country variants. The resulting gross solar gain (without application of utilisation factor to convert to ‘useful’ gain) is plotted in Figure 59 to illustrate the differences.

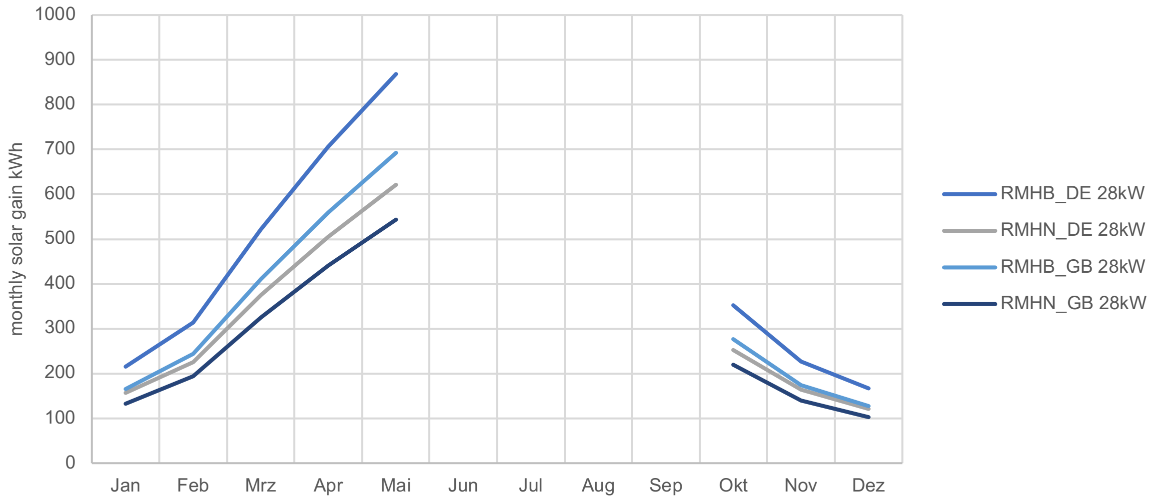


Figure 59: Monthly internal solar gains for DE and GB houses during heating period

It is worth noting that unlike the decreased heat loss that has resulted from the virtual renovation level and reduced U values, which includes changing the glazing properties from single to double glazing, the solar gain has conversely decreased due to the lower g-value of the double glazing used in the 'N' designated house representing glazing with lower transmittance and higher reflectivity associated with modern coating technologies.

From the simulation results, selected outputs were taken and analysed further. From the previous simulation chapters, it had been observed that with increasing PSR and cycling that the efficiency of the boiler had dropped. The boiler efficiency, heat delivered/gas consumed, were extracted to be compared with the theoretical boiler efficiency label rating. In the context of building fabric characterisation, and as preparation for the empirical data analysis section of this thesis, Power Temperature Gradients were plotted for all simulation variants, using the simulated gas consumption rate per month and the mean temperature difference (internal/external) the derived heat loss coefficient could then be compared with that of the BTSL input files.

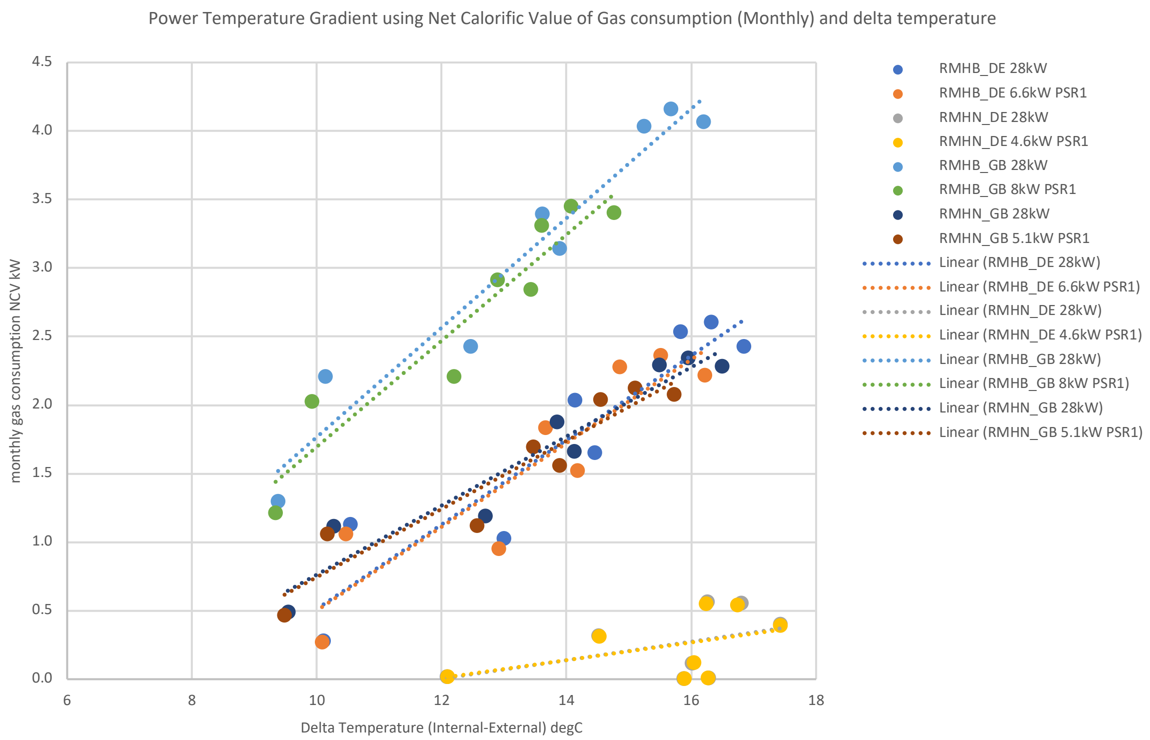


Figure 60: PTG plot of gas consumption (NCV) and delta temperature (internal-external), one data point per month

The PTGs are plotted in Figure 60 above, in this case using the NCV gas consumption as a measure of energy delivered. This follows the practical methodology followed by researchers with access to gas meter data but not heat meter data. A popular method due to the increasingly easy access to utility meter data as a form of non-intrusive data collection.

The best fit lines from which the gradients are taken for the heat loss coefficient do not change significantly between the PSR sizes when seen in the figure. The plotted correlations for RMHN_DE may be problematic due to some months with near zero energy consumption, an issue that may need to be considered when applying the PTG method to low and zero carbon houses in the future. The effective number of data points through which the best fit line is plotted for RMHN_DE is less than that for the other houses, effectively signalling a shorter heating season.

A summary table of the main results is shown below, comparing the input simulation parameters (building model HLC and boiler efficiency) with the simulation outputs of building heat loss from the PTG method and also the simulated boiler efficiency. The input boiler efficiency is taken from the test product from the Worcester ErP label (successor of SEDBUK) for a 28kW combi. To say what the efficiency would be for the fictional smaller boilers is not easy to say, therefore the same label is given to all, but greyed out for the PSR1 boilers to indicate the speculative nature of the value. The HLC is derived from the PTG plot shown later, in this case calculated from the gas consumption alone.

Table 19: Summary of input & output of BTSL simulations with house variants

	BTSL input				BTSL output			
House	**HLC (W/K)**	**SEDBUK NCV (%)**	**SEDBUK GCV (%)**	**Plant Size Ratio**	**HLC (W/K)**	**HLC R squared**	**Efficiency NCV (%)**	**Efficiency GCV (%)**
RMHB_DE	327	104%	94%	4.2	308.1	0.865	98.0%	88.2%
RMHB_DE	327	*104%*	*94%*	1.0	305.3	0.825	104.2%	93.8%
RMHN_DE	93	104%	94%	13	67.7	0.212	93.2%	83.9%
RMHN_DE	93	*104%*	*94%*	2.3	64.7	0.207	97.5%	87.8%
RMHB_GB	388	104%	94%	3.5	399.2	0.941	97.8%	88.0%
RMHB_GB	388	*104%*	*94%*	1.0	387	0.901	102.3%	92.1%
RMHN_GB	248	104%	94%	5.5	252.3	0.926	92.1%	82.9%
RMHN_GB	248	*104%*	*94%*	1.0	246.5	0.900	99.7%	89.7%

From the data presented in the table a similar trend of reduction in efficiency with oversizing is evident, as was seen in the previous simulations. The ideal conditions of boiler/house load matching can help a boiler achieve the rated efficiency from the ErP label. However, as was seen in the previous chapters, this will be at the expense of meeting setpoint temperatures on the colder days when operating within a standard two heating period daily programme, which can be counteracted with heat up optimisation leading to longer heating periods and little impact on efficiency.

Since the data suggests the same trend shown in the previous simulations, the PSR and boiler efficiency results were combined to produce the following chart. Theoretically, and in the eyes of SAP and the boiler energy label, the efficiency in all cases should be 94% (according to gas NCV).

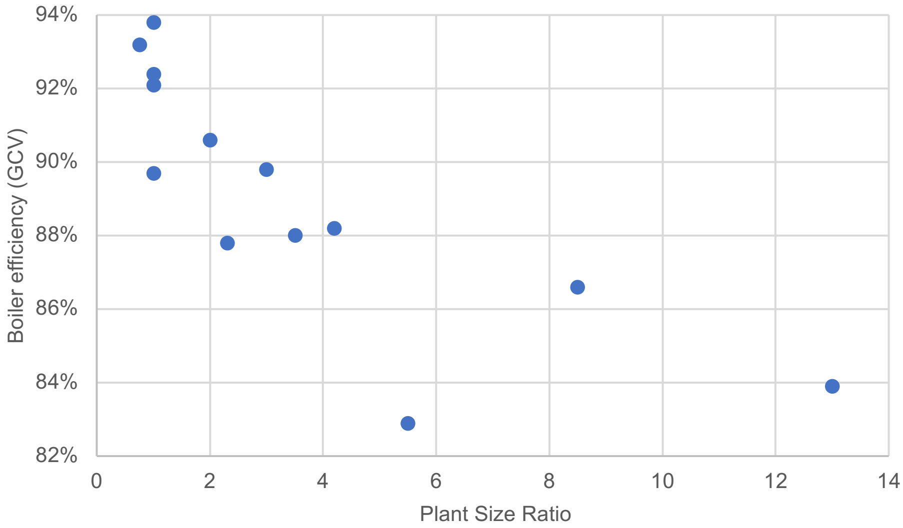


Figure 61: Boiler efficiency against PSR

It is clear from the simulation results presented that the increasing PSR is associated with decreasing operational boiler efficiency. Whether this relationship is robust enough to be a design indicator or SAP input parameter remains to be seen but more work in this area would help to improve technique. The interaction of heating system and building is complex, even in the controlled environment of simulation, where variables can be manipulated deliberately and in isolation, the results are not clear cut. From the selected houses and combinations simulated, PSR shows promise as a method for predicting boiler efficiency. In situ monitoring in the literature has shown that PSR is a contributing factor but not the defining driver of efficiency. PSR, on its own, seems to be too blunt a measure to accurately predict the propensity of a system to underperform. But as seen with the simulations, with different control strategies, more sophisticated technology does not seem able to compensate for sub optimal heating systems where PSR is too small or too big. Therefore, PSR should be considered in the evaluation of heating system performance on the evidence seen so far.

In a further investigation utilising the same simulation output data, the PTGs were replotted, but with the delivered heat as opposed to gas consumption. Although this is not an applicable method for determining building heat loss on the basis of gas meter data (smart or otherwise), it is of interest for the robustness of those gas demand-based methods to determine if boiler efficiency (with respect to flue gas losses and other non-useful losses), and therefore deviation between heat and gas demand, play a significant role in the predicted heat loss.

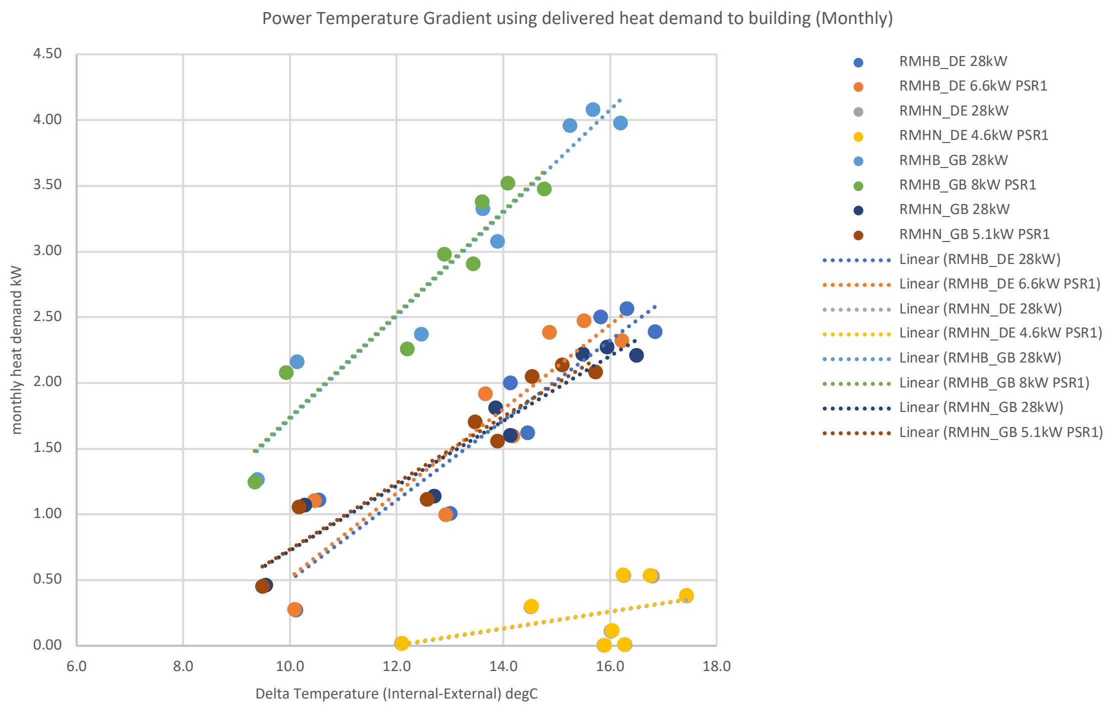


Figure 62: PTG plot of delivered heat power and delta temperature (internal-external), one data point per month

The resulting building heat loss coefficients are summarised in the table below, together with the original BTSL input HLC and the values derived from gas consumption data from the simulations.

Table 20: HLC values from PTGs of gas and heat demand

	BTSL - model inputs	BTSL – simulation outputs	
House	**HLC (W/K)**	**HLC (W/K)** **Gas demand**	**HLC (W/K)** **Heat demand**
RMHB_DE	327	308.1	304.1
RMHB_DE	327	305.3	320.5
RMHN_DE	93	67.7	64.2
RMHN_DE	93	64.7	63.8
RMHB_GB	388	399.2	392.1
RMHB_GB	388	387	392.2
RMHN_GB	248	252.3	246.8
RMHN_GB	248	246.5	252.5

Despite noticeable and expected variation of boiler efficiency evident from the simulations, the same cannot be said for the difference in HLC depending on whether gas or heat data is used. Certainly, neither of the methods can be said to have consistently delivered a more accurate HLC compared to the BTSL input value.

Sometimes the HLC is larger and sometimes small when using heat rather than gas as the input parameter. This may reflect the relative inaccuracy of plotting a PTG through just 8 points, as well as the variation in efficiency, month to month, which can be different in the various houses. As mentioned earlier, for RMHN_DE, some of the data points fall along the lower limit of heat input to the building, and can make the PTG curve less accurate and the efficiency in those months difficult to gauge accurately. However, this is a brief diversion into this topic and would certainly warrant bearing in mind as the PTG method (Section 2.4.1)develops and becomes a possible methodology in future virtual or consumption-based building assessments.

Making assumptions for parameters which are not readily measurable has been a feature of epidemiological energy studies, such as those which attempt to determine internal temperatures from building age (Chambers, 2017); therefore, an exploration of what could be implied from gas meter data alone is of value to future researchers. Although PSR seems to play a key role in the efficiency which the boiler delivers, the dynamics of the boiler behaviour manifest themselves as cycling; this could be implied from higher frequency gas meter data by indirectly monitoring the number of boiler starts which would be characterised by peaks in gas demand. In the following chart the number of boiler starts per hour of operation (as defined by the heating schedule) has been plotted against efficiency of the boiler system.

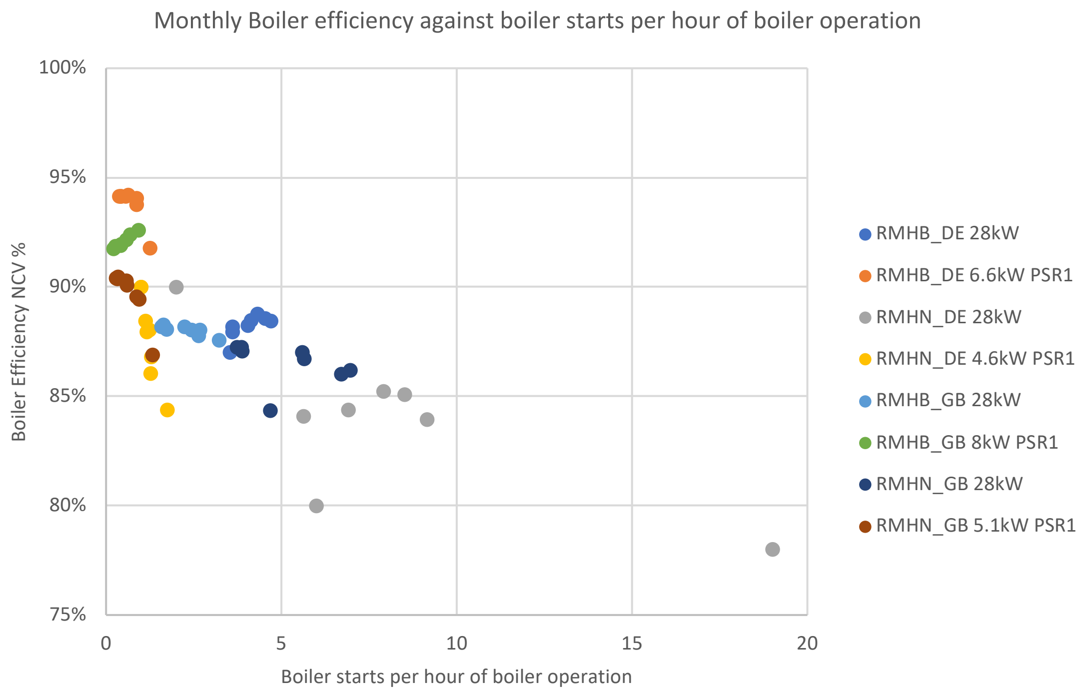


Figure 63: Boiler efficiency against boiler starts per hour

Although not a consistent predictor of efficiency when considering just one of the boilers simulated, when aggregated together in the chart there seems to be a clear trend to decreasing efficiency as the number of starts per hour, i.e. cycling, increases, in line with the other findings so far.

In previous boiler trials such as the Energy Savings Trust/Gastec in situ report (Orr et al., 2009), a correlation was seen between total heat supplied per month and the measured efficiency. A similar trend was seen with the extensive RHPP Heat Pump Case Study Report plotting the drop in COP at low (<0.2) monthly load factor (Lowe et al., 2017a).The chart showing the relationship for boilers from the EST study has been reproduced in Figure 64.

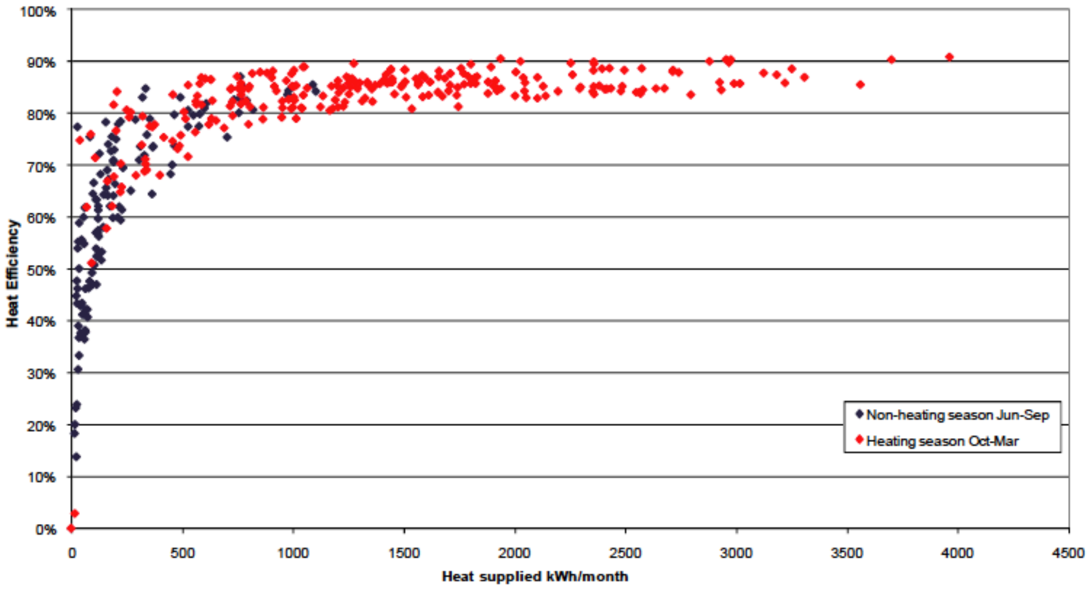


Figure 64: Efficiency and heat supplied (Orr et al., 2009)

The field monitoring represented by the data in Figure 64 spans both the traditional heating season and non-heating season. It was observed that the efficiency drops dramatically at the lower heat demand months, which mostly corresponded to non-heating months. The simulation data presented here is limited to the heating season but as can be seen from Figure 65, there is some similarity at the lower end of the heat demand spectrum. A spread of efficiency of almost 10% is seen both in the field data (Orr et al., 2009), as well as the simulated data. In situ monitoring saw normal efficiency levels (when consumption was more than 500kWh per month) between 80% and 90%, whereas in simulation the figure was between 85% and 95%.

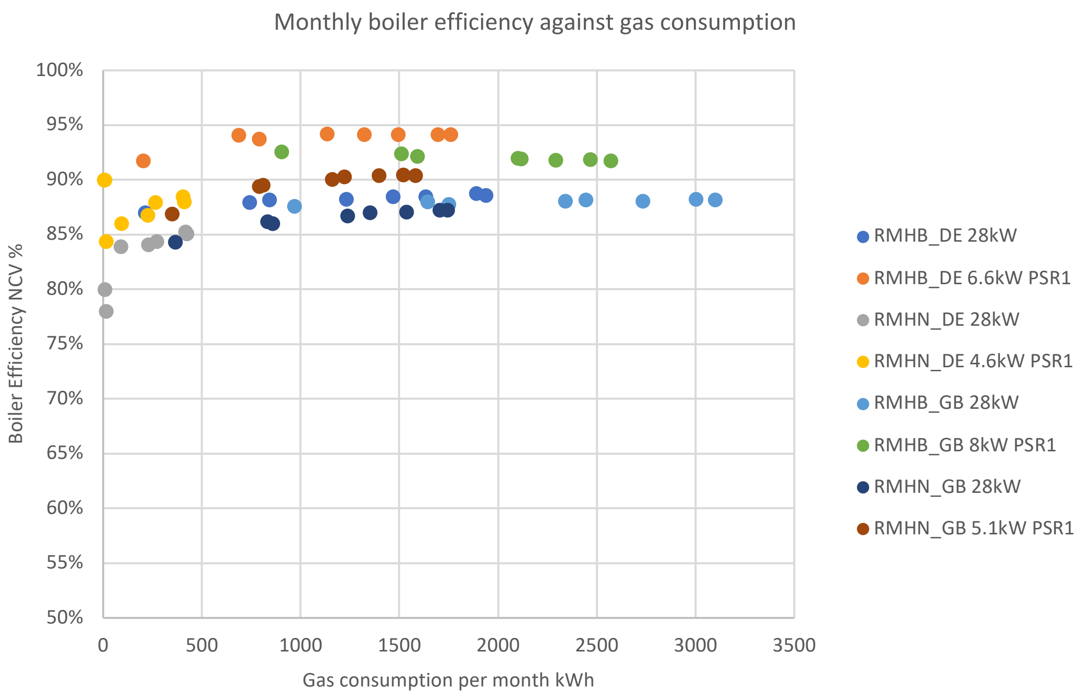


Figure 65: Monthly gas consumption against boiler efficiency

In summary, BTSL simulations with a fixed heating system, but varied house types and plant sizes have shown more of the same trends seen in previous simulations. Increasing plant size ratio seems to be detrimental to boiler efficiency, moreover the symptom of boiler cycling shows a stronger link to system efficiency. Both parameters could form useful tools in the identification of a heating system's ability to perform well. Plant size ratio could be better integrated into SAP calculations and boiler commissioning requirements. Fine time scale gas meter measurements could be used to identify cycling in the system and infer efficiency as part of low intrusion field monitoring research activities.

6 Empirical data results

As outlined in the methods (section 4), the cross-model comparison is complemented with real world data from heating systems, Dataset A contains high frequency EMS boiler data (section 4.3.2) and sensor data from 4 case studies in the UK and Germany. From the simulation results, the effect of dynamic behaviours of boiler systems (cycling and intermittency) on efficiency was seen and the important role of PSR was also identified. By analysing the data, the dynamic effects highlighted so far can be corroborated and elaborated upon with a view to understanding their occurrence in real buildings. Dataset B expands the analysis to 217 heating systems while focussing on the boiler data only. This allows for a more wide-ranging analysis to look for trends in the wider building stock.

6.1 Empirical Dataset A: Building & heating system case studies

Besides the description of the buildings, their heating systems and the data map (Figure 31) given earlier in section 4.3.3, a more detailed summary of the heating schedule is presented in the table below.

House	UK1	UK2	UK3	DE1
Schedule	*Mon-Sun:* 0600-0930:22°C 0930-1200:10°C 1200-1230:22°C 1230-1415:10°C 1415-2200:22°C 2200-0600:10°C	*Mon-Sun:* 0600-0930:18°C 0930-1130:16°C 1130-1330:17°C 1330-1600:16°C 1600-2200:18°C 2200-0600:16°C	*Mon–Fri:* 0500-0730:18°C 0730-1630:12°C 1630-2200:18°C 2200-0500:15°C *Sat–Sun:* 0600-0830:18°C 0830-1600:12°C 1600-2200:18°C 2200-0600:15°C *Hot water Mon-Sun:* 0630-0830 1630-2230	*Mon-Thu:* 0500-2200:21°C 2200-0500:16°C *Fri:* 0500-2300:21°C 2300-0500:16°C *Sat:* 0600-2300:21°C 2300-0600:16°C *Sun:* 0600-2200:21°C 2200-0600:16°C

Table 21: Empirical Dataset A heating schedules summary

The monthly mean internal temperature variation of all measured houses is shown in Figure 66, Figure 67, Figure 68 and Figure 69, all of which have been plotted with the same y and x axis scales. At least one internal temperature from the main living space (and location of the room thermostat) was measured in each dwelling while the boiler EMS data was logged. Since this temperature represented either the living space, room thermostat position or both then it was a useful measure when looking at boiler response trends, but for determining building parameters such as heat loss then it was deemed not to be a reliable representation of the whole building internal temperature. Additional sensors were placed in all houses within the restrictions of access, time and budget. A weighted average internal temperature is shown as a solid grey plot, the weighting was according to the floor area of the measured room in relation to the total measured area, which could vary according to the live measurements for that month.

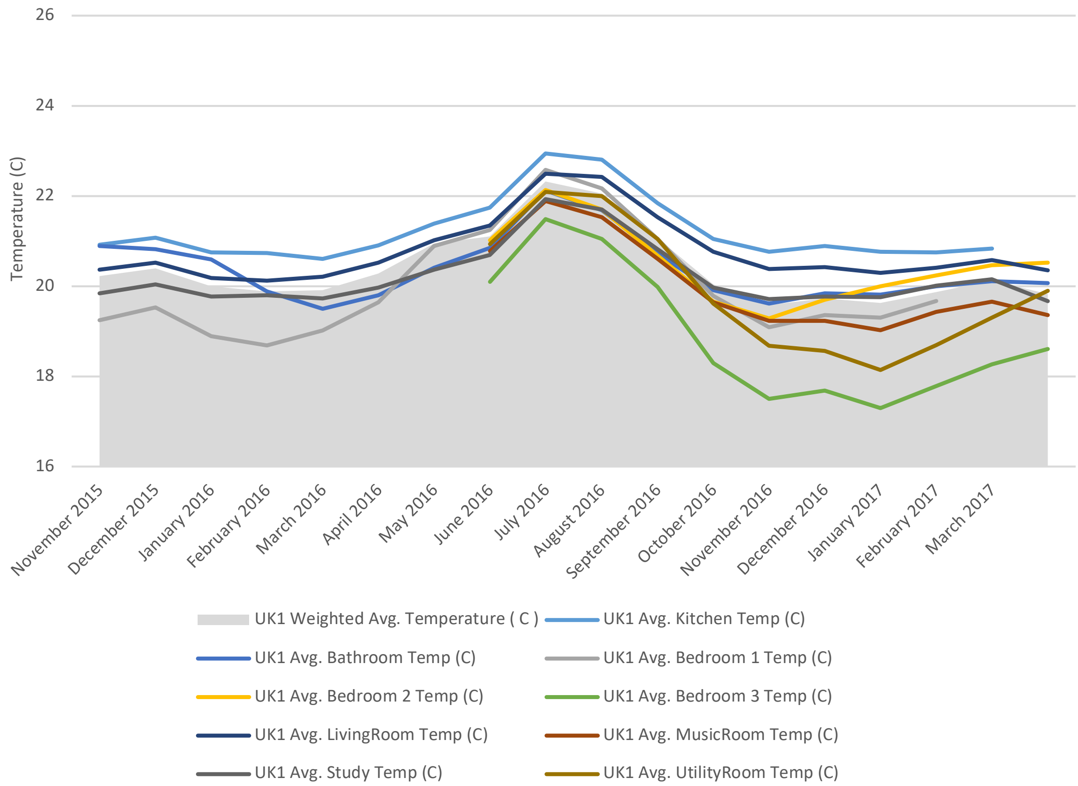


Figure 66: UK1 Internal monthly temperatures

UK1 was the building with the longest and most detailed temperature measurements of all recordings. The kitchen temperature was consistently the highest measurement in the building, corresponding also to the largest floor area and the location of the thermostat control. Bedroom 3, once a sensor was placed there in June 2016, was consistently the coldest room in the building; on consultation with the occupants, this was found to be because the main one (Bedroom1) was used daily, Bedroom2 was used intermittently by guests and Bedroom 3 was very rarely used and the door was therefore kept closed with the radiator TRVs turned to a low setting.

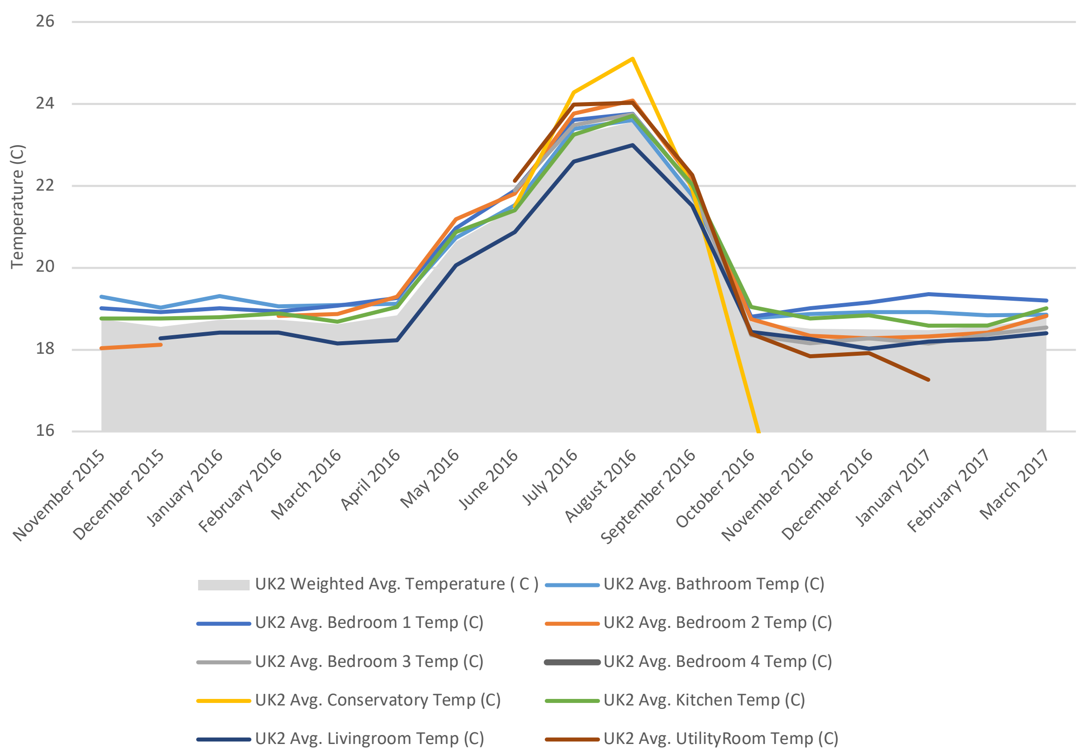


Figure 67: UK2 Internal monthly temperatures

In contrast to UK1, recorded heating season temperature sensor readings were generally lower, 18-19°C, compared to 19-21°C, in line with the similarly reported thermostat setpoints shown in Table 21. The variation between room temperatures is not as marked with the exception of the conservatory which underwent renovation between 19th Jun to 18th July 2016 resulting in a disruption in the measurements. Also, the removal of a small radiator in the space bringing it in line with building regulations (HMGovernment, 2018) and making the space unheated resulted in the low recorded temperatures in the winter months of 2016/17. For this reason, the conservatory temperature measurements are not included in the weighted average for UK2, since it ceased to be part of the heated floor area. Summer temperatures in UK2 exceeded those of UK1, indicating either higher levels of solar gain, possibly supported by the conservatory, or a lower overall heat loss, either fabric or ventilation.

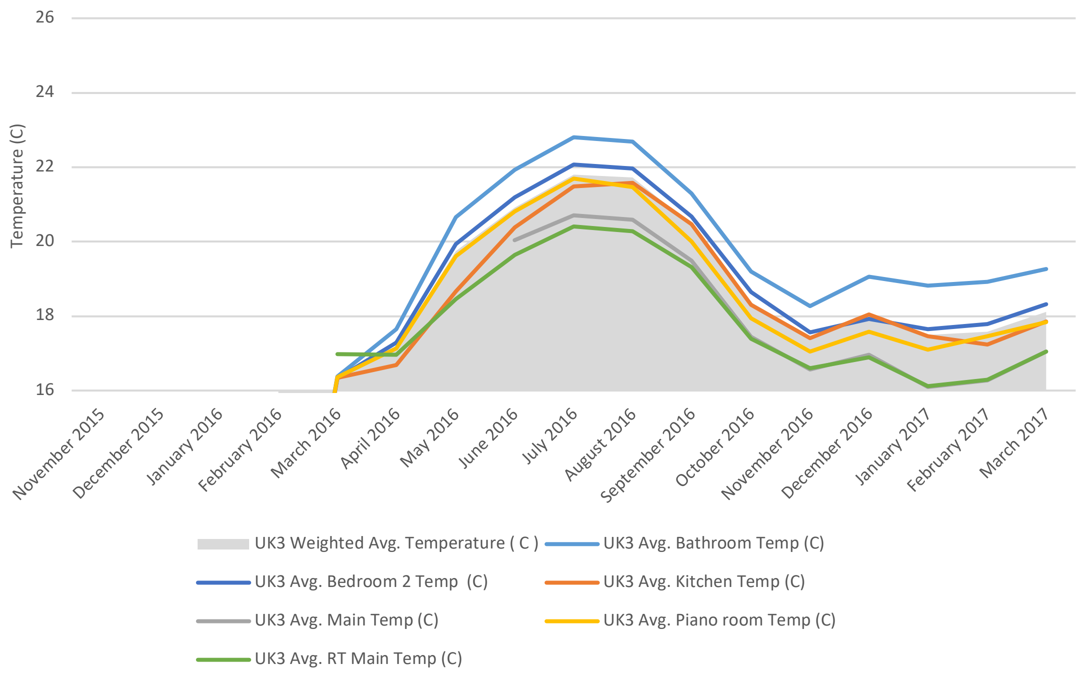


Figure 68: UK3 Internal monthly temperatures

In the UK3 house it was noticed that there was a delay in transporting and installing the temperature sensors in February 2016, that month's temperature data will not be used in further calculations in this thesis.

Although the heating system control setpoint of 18°C was common to UK2 and UK3, UK2 exhibits a higher level of temperature homogeneity across rooms. UK3 bathroom and stairwell (Room thermostat location) are up to 1°C above and below the other rooms and the weighted average for most months. That the bathroom is consistently higher cannot be explained by solar gains in this case, since it is located on the north side of the house, but a consistent boost to the heating in the bathroom due to the DHW, or supplementary electrical heating is also possible such as an electrically heating towel rail.

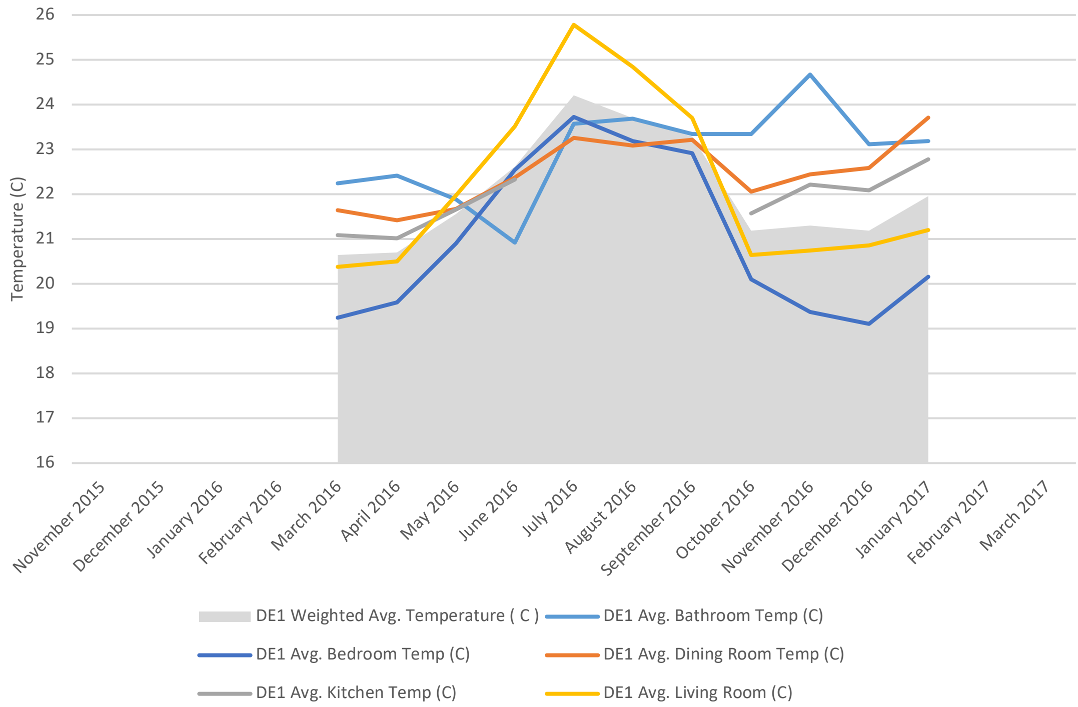


Figure 69: DE1 Internal monthly temperatures

DE1 recorded the highest internal temperatures and also the most overtly erratic. The bathroom temperature bucked the trend of the rest of the house in June and November 2016 possibly due to a higher tendency in this space to alter radiator settings and open windows. In the process of weighting and averaging the temperature measurements the volatility of the bathroom measurement was smoothed out since the room was small at just 4.3m^2 and less than 8% of the measured floor area. It was also brought to the researcher's attention during the measurement phase that a small wood burning stove was located in the dining room, the homeowner insisted that it was used only sparingly so the measurements remain, but this additional heat source will be borne in mind in the upcoming analysis.

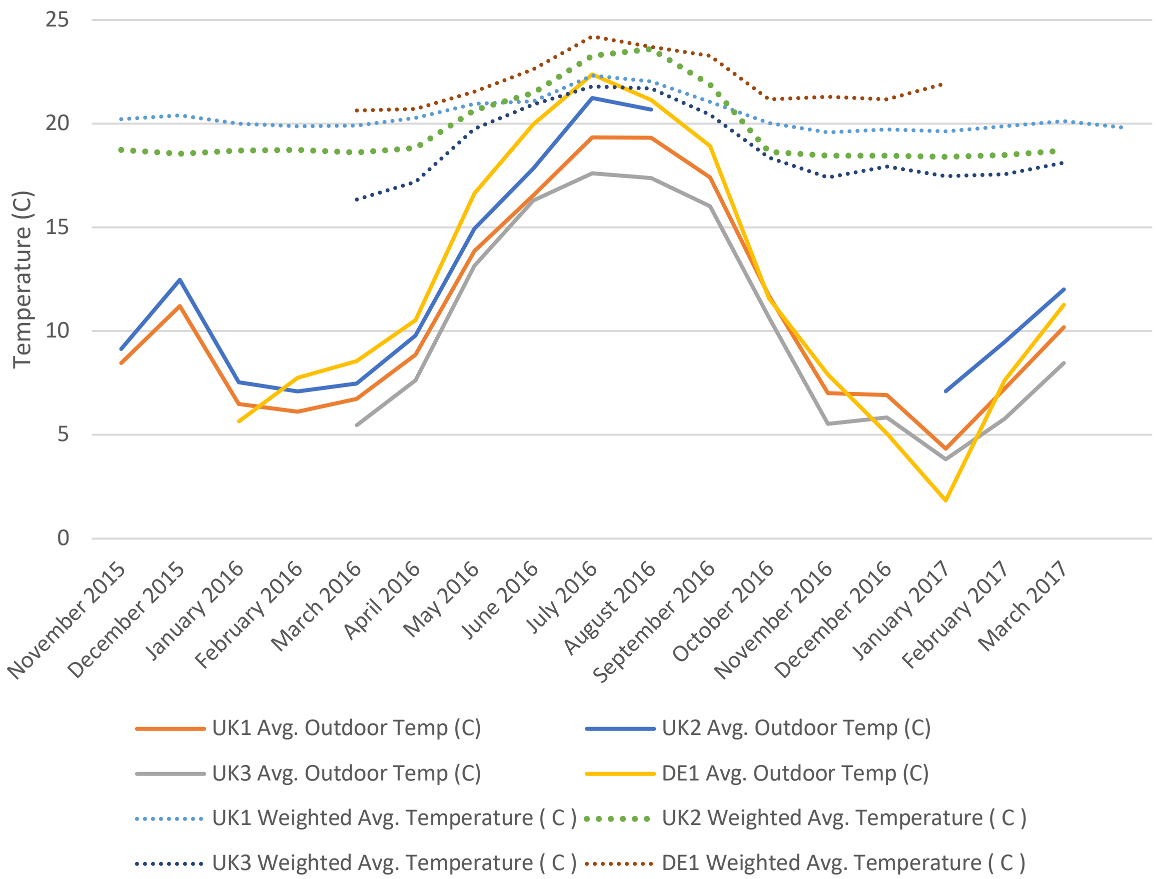


Figure 70: Dataset A, indoor & outdoor monthly temperatures

In Figure 70 the floor area weighted internal temperatures and the available outdoor temperature measurements from each location the data are plotted. The relatively mild December of 2015 is mirrored in both UK1 and UK2 whereas DE1 experienced consistently warmer weather except for January 2016 and 2017.

Building UK1 and UK2 were in neighbouring towns and as such have similar average outdoor temperatures, whereas UK3 was further north, but all these UK houses can be considered to be in the midlands of England, and DE1 in the southern half of Germany in the state of Baden Württemberg. The outdoor temperature sensors were connected to the weblogger device and therefore the external temperature of UK2 is missing from August 2016 to January 2017 due to the aforementioned technical interruption to the weblogger service at that location.

Turning from the measured temperatures to the energy demand data is limited to the recordings made via the Loop service (Navetas, 2017) in UK1 and UK2 presented in Figure 71.

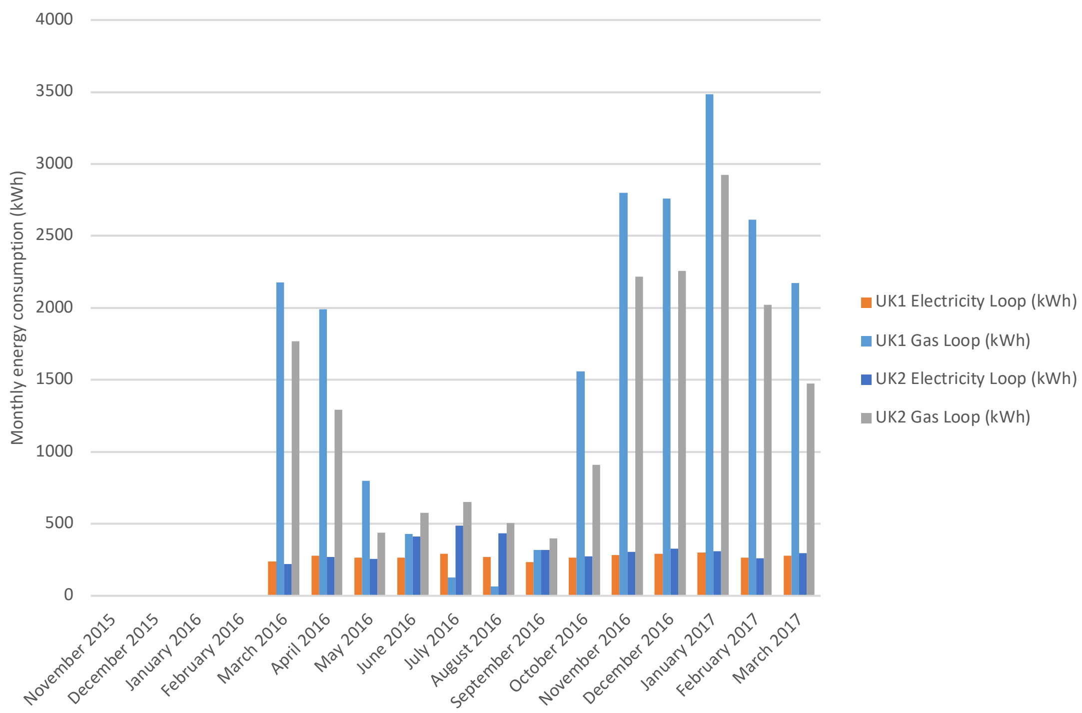


Figure 71: Energy demand in UK1 and UK2, gas and electricity

Data recorded during the heating season shows a higher gas consumption in UK1 reflecting the larger size, floor area and probably also the thermal properties of the older building. However, in summer the gas consumption of UK2, in contrast to UK1, increased from May to July 2016 before reducing again in September. This local peak of gas demand could go some way to explaining the higher summer temperature in UK2, since the gas could only have been used by the boiler (heating and hot water) or for increased cooking activity. Electricity consumption follows the same summer trend in UK2, contrasting with stable electricity demand in UK1 all year round. The differing occupancy of UK1 and UK2 may form part of the explanation as to why the summer energy demand differs in this way, but this is a complex socio technical system (section 2.2) and the absolute levels of consumption are not as important in the analysis as the performance of the heating system. The data will also be used to characterise the building heat loss in section 6.1.6.

6.1.1 UK1 day profile

Although comparing monthly average temperatures and energy consumption over a year period shows one aspect of the building heat energy demand, to try and understand the heating system and how future systems can be implemented one must look into the detailed (<1minute interval) measurements. A week at UK1 is shown in Figure 72, with 8 measurements (7 from boiler EMS and 1 temperature sensor) over a week which give a good starting point for analysis. The blocks of boiler activity for each of the 7 days can be seen in the *Actual Boiler Power, Supply Temperature and CH mode flags,* reflecting the reported day time only heating schedule. At this level it is clear that boiler power levels are not stable during the heating period and from the CH mode Flag, 1 indicating boiler operation mode in Central Heating (a DHW equivalent is also recorded as DHW mode Flag), it would seem that a great deal of on/off switching of the boiler heating is occurring. A closer look at the daily level should be useful to unpick the behaviour in more detail.

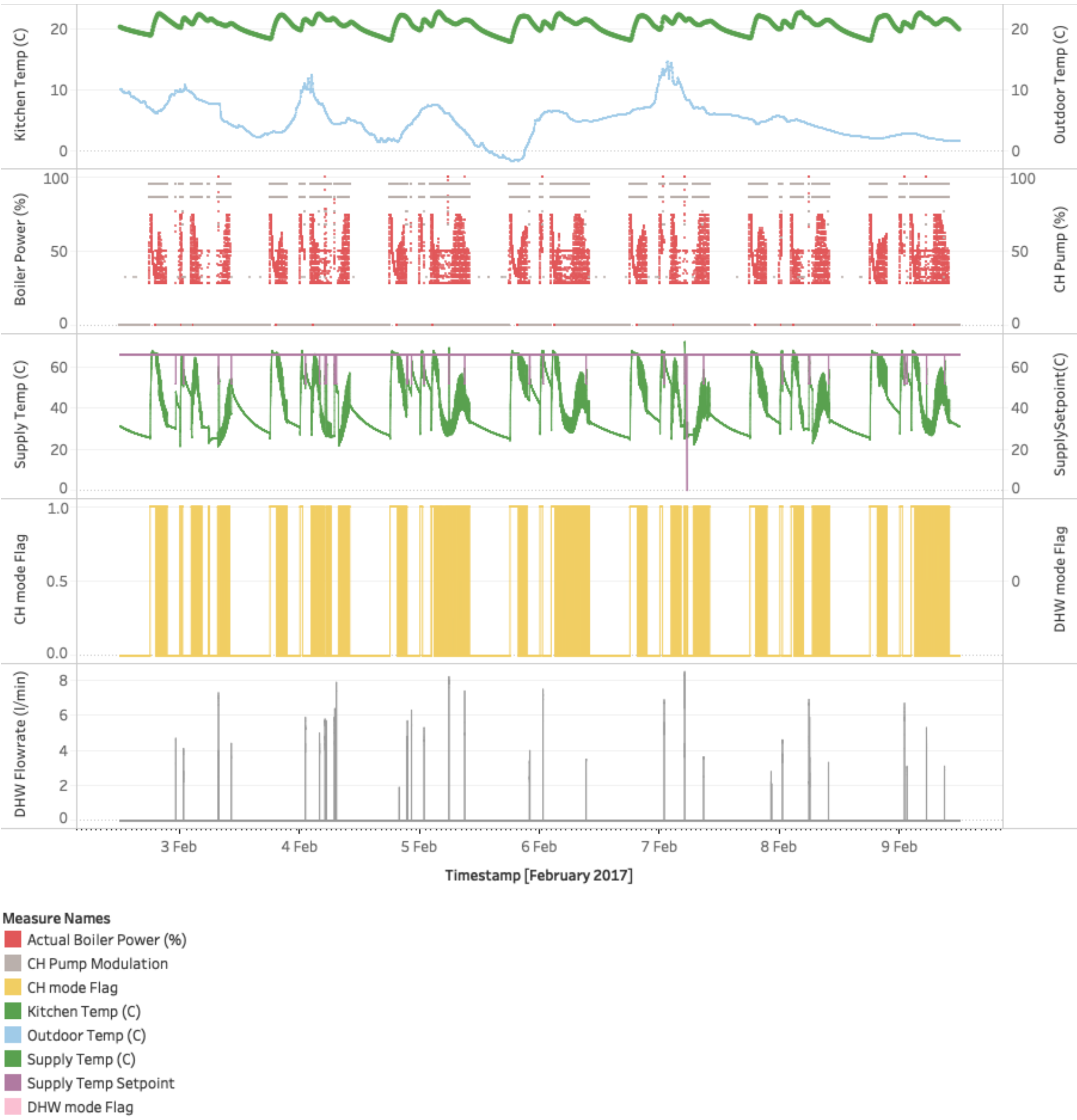


Figure 72: Building UK1 winter week profile (selected channels)

In Figure 73 a winter day profile is shown for UK1 building, the day was 3rd Feb 2017 (first day from the previous weekly chart); winter days have been used at this stage to highlight boiler phenomena and building specific behaviour.

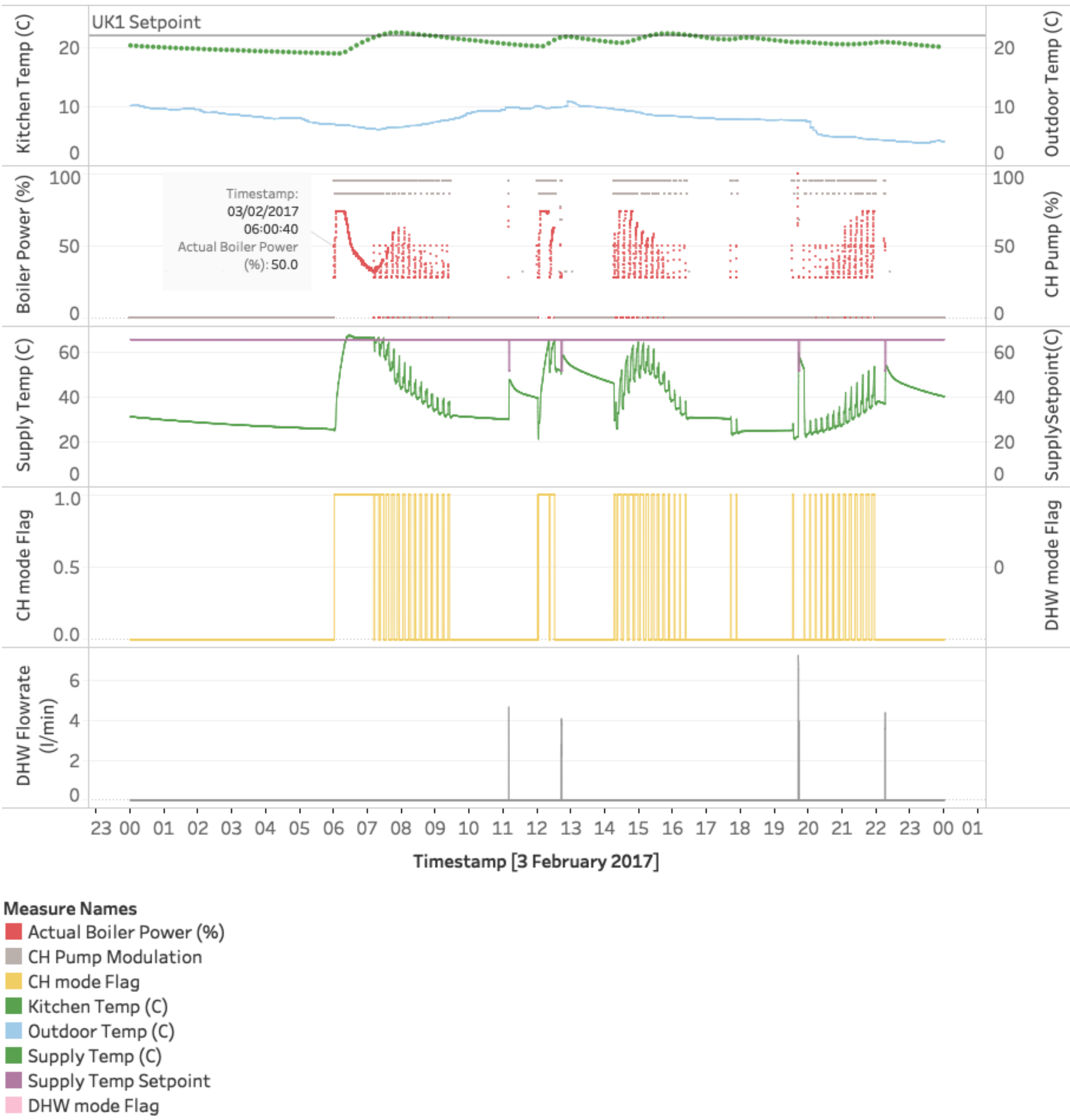


Figure 73: Building UK1 winter day profile (selected channels)

The uppermost chart shows the internal temperature measurement in the main heated space (Kitchen), which is also the location of the building thermostat. The temperature measurement in this case is not taken from the thermostat itself since, although it measures temperature, it was not logged and the only output was a relay signal to the boiler. From the internal temperature alone the most basic estimation of the heating behaviour can be seen. The temperature falls gradually from the start of the measured period at 00:00 until shortly after 06:15 when an increase begins to take place over a period of 2 hours: the temperature rises by 2.5°C indicating that space heating is in operation (supported by the boiler data to come), before a brief stabilisation phase there follows a further gradual decline until 1230 when another heating operation takes place. From 1500 onwards, the temperature is kept stable until 2200 when the temperature again begins to drop as the daily heating schedule comes to an end. The exact times of heating operation are only roughly identifiable from this internal temperature data alone, but moving into the EMS boiler data helps remove the uncertainty and add another dimension to the understanding of the heating behaviour.

The Boiler Power/CH Pump trace shows the boiler power signal as taken directly from the EMS data stream of the boiler control. This power signal indicates the percentage of the rated maximum heat output the boiler is currently operating at, in this case 100% represents 42kW. The data is plotted as points only with no interconnecting interpolating lines to highlight that the boiler modulation is not continuous, boiler range and modulation is not possible below 28% and is also granular with distinct modulation steps. Considering the temperature increase seen in the kitchen from the DHW Flow rate trace it is now clear that the boiler was operational shortly prior to the initial rise in temperature starting at 06:00 (as expected from the programmer schedule). It is worth noting again here that the maximum power output of this model of boiler is not the maximum power output for central heating, which is limited to 30kW. The 42kW is reserved only for hot water production, therefore the initial power peak seen at shortly after 06:00 is at 74% of the boiler maximum which represents 100% of the central heating maximum power. The DHW power can be seen more clearly at the short peak at 11:09, this can be clearly identified as a DHW operation by the DHW flowrate measurement shown in the bottom trace, accompanied by a lower supply temperature setpoint of 52°C in order to achieve the desired DHW flow temperature. From the boiler power data, the heating schedule and the boiler reaction to heat demand can be seen with a greater resolution than merely the room temperature, or the central heating water temperature (shown in traces 2 and 3 from the bottom). The corresponding boiler operations to the reported heating schedule can be seen at 06:00-09:30, 12:00-12:30 and between 15:15 and 22:00. However, 4 additional boiler operational phases can also be seen throughout the day, corresponding to the DHW flow rate demand seen in the bottom chart. A secondary confirmation of boiler operation type can be made by looking at the 'CH Flag' data which indicates when the boiler is operating for fulfilment of a heating demand; a similar flag for DHW was also logged but has been omitted since it duplicates the flowrate data in this figure. The CH flag is not a direct measurement of the heating demand communicated by the room thermostat relay, although that does form the basis of the CH flag parameter. Additional internal boiler algorithms are calculated to determine whether the boiler can/should deliver central heating, going beyond what the thermostat can determine alone. For example, a supply temperature above the user defined setpoint (controlled by the user via knob on boiler control) would result in the CH flag going to 0, even if the room setpoint temperature may not have been reached. Such a situation could be caused by numerous heating circuit conditions such as limited heat transfer capacity of the radiators (in this case the radiator capacity is approx. 70% of the boiler rating), which can be exacerbated by closing of TRVs leading to a level of hydraulic restriction in the heating circuit which throttles the ability of the boiler to deliver heat, leading to a steep rise in supply temperature and efficiency penalties (section 2.3.3).

Additionally, in Figure 73 the temperature of the supply water from the boiler is shown, adding another dimension to the heating system operation, bridging the gap between the rate of gas combustion, as represented by the boiler 'actual power', and the actual heat delivered to raise the internal building temperature. It was not possible to measure the flow rate of the central heating water, so calculation and confirmation of the energy transported from the boiler to the heating circuit is not possible. However, the supply temperature does act to show the way the boiler is operating to meet the heat demand, which in the case of simple controllers is only a binary signal. Conflicts in the control algorithms can be seen when internal supply temperature setpoints are not reached but the call for heat is terminated, or vice versa, both of which can be problematic for room temperature control and gross efficiency.

Having looked at the data at the level of a day gives a general view of the boiler behaviour to heat demand, but it is not clear what is happening within the heating period, in particular the cycling behaviour which begins after the initial morning warm-up phase a feature that was seen during simulations in
Simulation B: Plant Size Ratio, Simulation C: Heating System Control and Simulation D: House, thermal mass & heat loss, which highlights that the similar cycling and PSR driven behaviour may be present here also. The boiler power level is clearly not constant during the heating schedule (from the programmer), nor the heat demand phases (defined by CH Flag=1) and is modulating across the complete range of CH power output levels. This is also reflected in the supply temperature variation which, although not constant, has a similar bandwidth of variation. To understand which events are happening concurrently and why the boiler seems to be varying its thermal output so widely and frequently a deeper look at a shorter time span is necessary.

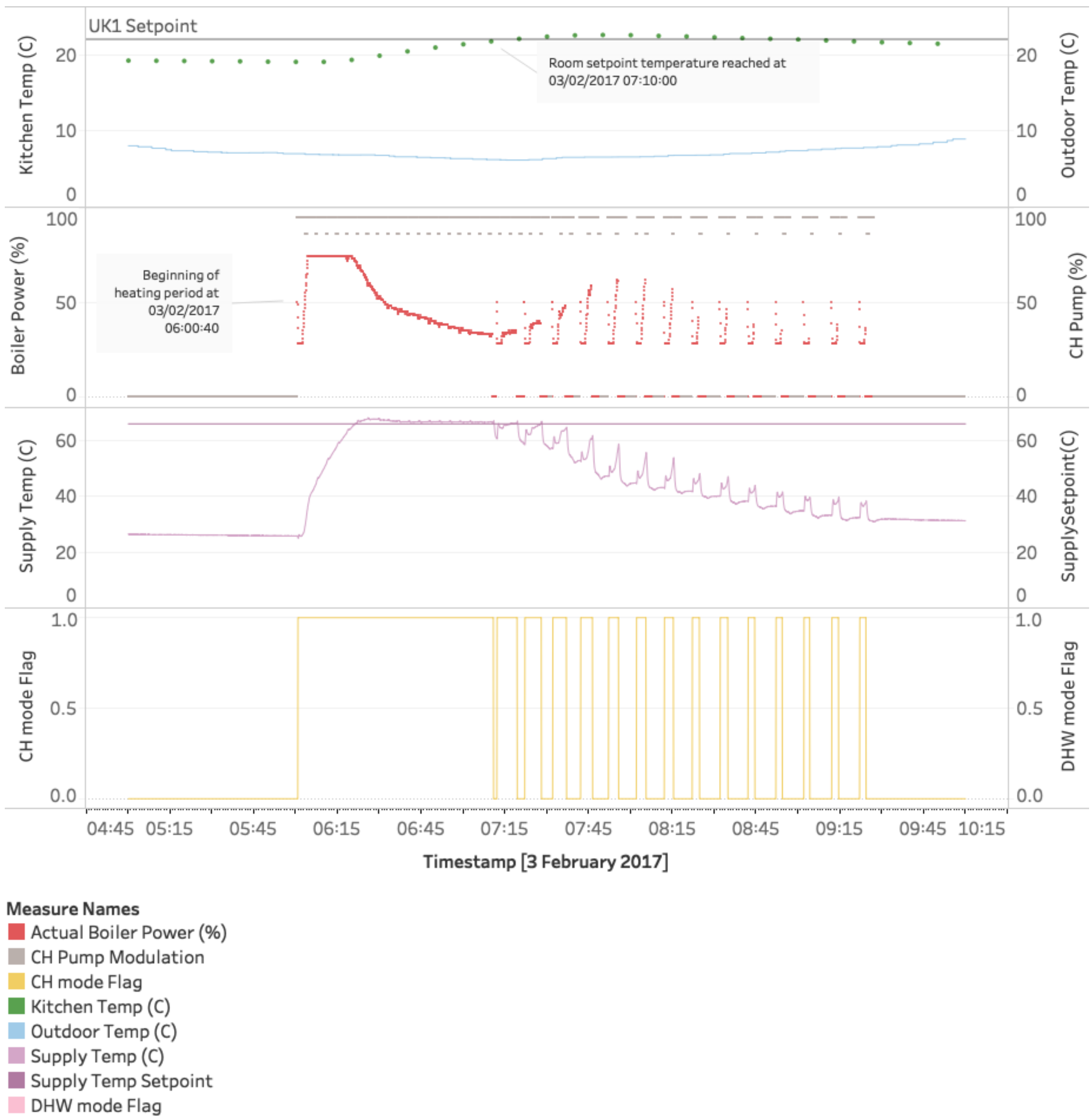


Figure 74: Building UK1 winter morning profile (selected channels)

In Figure 74, only the morning heating period is shown, with the same channels as the previous figure. Two moments have been highlighted, namely: the beginning of the heating period and when the indoor temperature has reached the required UK1 indoor setpoint. On the selected day (3rd February) this took 1 hour 10 mins, just over one third of the time for which the heating is programmed for the morning period. However, looking at the boiler power it can be seen that without reaching the minimum power modulation that the boiler also stopped operation around 07:10. The average power input of the boiler during this morning operation period is 25% or 10.8kW, below the minimum modulation of the installed boiler. It starts operation at the programmed maximum of 30kW (72% of appliance maximum) and then modulating down, not because the room temperature has been reached as the boiler receives only a binary input demand, but because the boiler defaults to controlling the set CH supply temperature, in this case aiming for 66°C. The CH supply setpoint temperature is a user defined supply temperature setpoint, normally set via a dial on the front of the boiler, which has a maximum value of 80°C and can be read from EMS data stream. In this case the available radiator capacity of almost 22kW should not be a limiting factor unless the radiator capacity or TRVs are restricting the flow due to being set at a lower temperature than the room thermostat, the available radiators without TRVs act as a bypass in that case but have only a 3kW capacity. The end of the warm up period, i.e. when the room temperature is reached, closely corresponds to the beginning of a period of boiler cycling. The first ON/OFF cycles of the boiler from 07:00 are characterised by a short initial spike in the boiler power followed by a period of low-level operation corresponding to maintaining the setpoint supply temperature at 66°C. The initial peak is part of the standard start up procedure of the boiler, where the ignition and stable flame are ensured through the modulation level going to 50% then dropping to minimum over a period of 20 seconds, then maintaining that level for a further 1.5 minutes (see Figure 75).

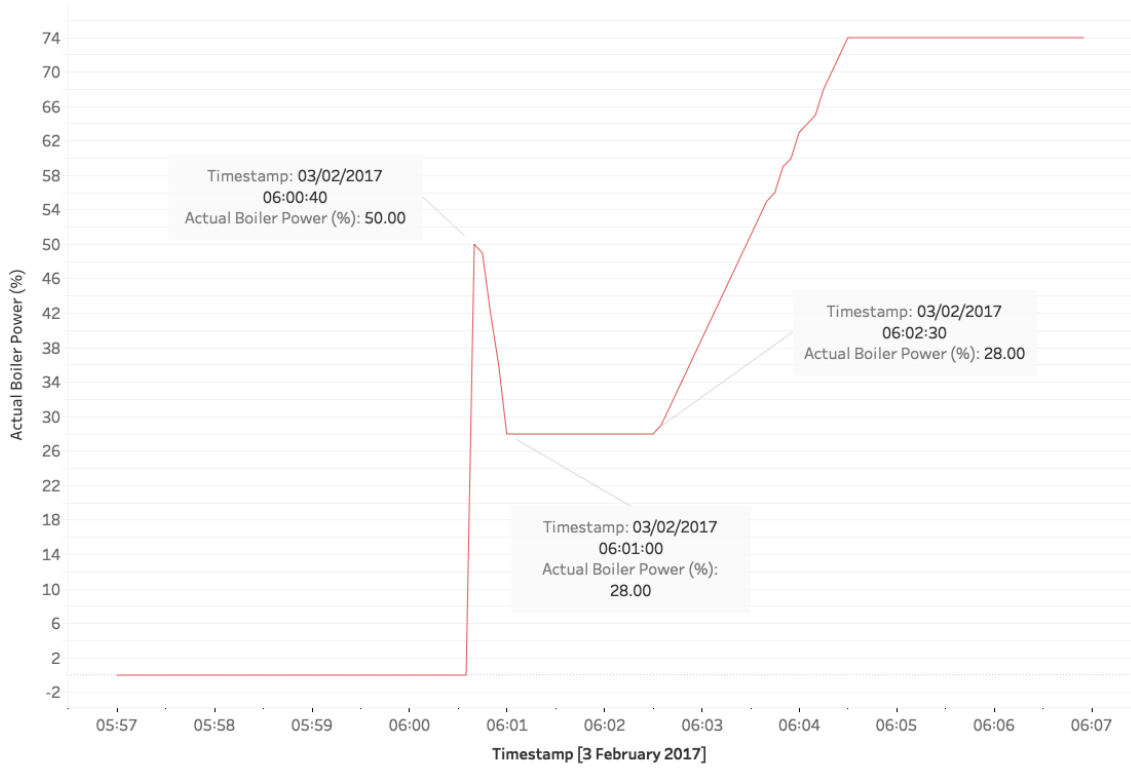


Figure 75: Start-up behaviour of boiler from UK1

Subsequent ON/OFF cycles differentiate themselves in terms of the ramping up of power towards the end of the cycle. The boiler continually tries to reach the supply temperature setpoint but is stopped short by the room thermostat when it reports the room temperature is satisfied or the boiler determines that the supply temperature is rising too rapidly. This can be an indication of either CH circuit blockage (e.g. by closed TRVs or by radiator capacity saturation) or insufficient heat demand, and therefore CH mode flag is set to 0.

The cycles of the boiler between 0710 and 0930 seem to share some similar characteristics, besides the start-up procedure just described. The cycles are relatively short (up to 4 minutes of boiler burner operation) and are all accompanied, as expected, by CH pump operation, to move the heated water to the building CH circuit. However, all cycles also show a few minutes of CH pump 'overrun', meaning that after the CH flag has gone to 0 and the burner has been switched off, the pump continues to run as marked by the CH pump modulation channel, plotted on the secondary axis alongside burner power modulation. This overrun function operates for approximately 3 minutes and works to reduce the supply temperature through continued heat transfer to the living space and thereby boiler overheating. The boiler is programmed with a so called 'anti-cycle' function as standard, with a user input variable, although not directly on the boiler interface, which governs the minimum time between consecutive CH demands, in UK1 this was set to 7 minutes.

The rapid increase in boiler power which takes place at the end of cycles between 0730 and 0840 may seem surprising given that the room temperature is close or at the setpoint, but knowing that the room thermostat lacks sophistication makes this behaviour explicable. The boiler is essentially blind to the absolute room temperature, setpoint and outside temperature, not to mention the building heat loss coefficient. The control, in this case, has distilled all that information into a binary call for heat transmitted by the switching of a relay. Therefore, the boiler, unaware of the magnitude of temperature deficit or current heat loss, seeks only to achieve the internal target of supply temperature setpoint by increasing the burner modulation. This type of simple room thermostat control is designated ErP Class I and constitutes the minimum allowable control according to UK Building regulations, it would be considered efficiency neutral in SAP calculations. But as seen here such controls can lead to control conflict and undesirable boiler operation leading to underperformance as predicted in simulation (section 5.3).

To alleviate the cycling behaviour caused by crude control mechanisms, more sophisticated controls could alter the supplied heating water temperature based on outdoor temperature (known as a 'heating curve' and used as a proxy for building heat loss) and/or limit the thermal power depending on the proximity to the desired setpoint through standard control algorithms such as PID (Proportional-Integral-Derivative).

The later cycles, from 0845 onwards, still show the same rise in boiler power level. The duration is shortened (2 mins versus 4 mins) and the associated rise in CH supply water temperature is shallower. This points towards a manifestation of 'bang-bang' control brought about, not just from the room controller simplicity, but from the minimum modulation output of the boiler being too much for the current building heat load, therefore satisfying the heat demand within a matter of minutes which switches the room thermostat. A wider controller hysteresis, lower boiler modulation level or smaller boiler rating would help to alleviate this symptom, although only the latter two could ensure no impact on customer comfort. At this stage the heat load of the building is not known, but with the help of the data collected here an estimate of the heat loss, for this and the other case studies, will be made in section 6.1.6. Then the disparity between boiler minimum load and current building heat demand can be analysed in more detail (section 6.1.7 and 6.1.9).

6.1.2 UK2 day profile

UK2, like UK1, has a combi boiler installed and ostensibly, from the point of view of space heating, the story looks similar to that of UK1. Besides the lack of a midday heating period, as determined by the reported programmer schedule, the main sequence of boiler events looks similar. There is an initial start-up burner procedure followed by ramping up the power until an eventual satisfaction of heating/supply temperature demand then the repeated ON/OFF cycles. What differs significantly to UK1, is the interplay of CH and DHW operations, the latter being mostly absent in UK1. Figure 76 shows the difference in activity characterised by the increased supply temperature variation and also the densely recorded CH and DHW flags.

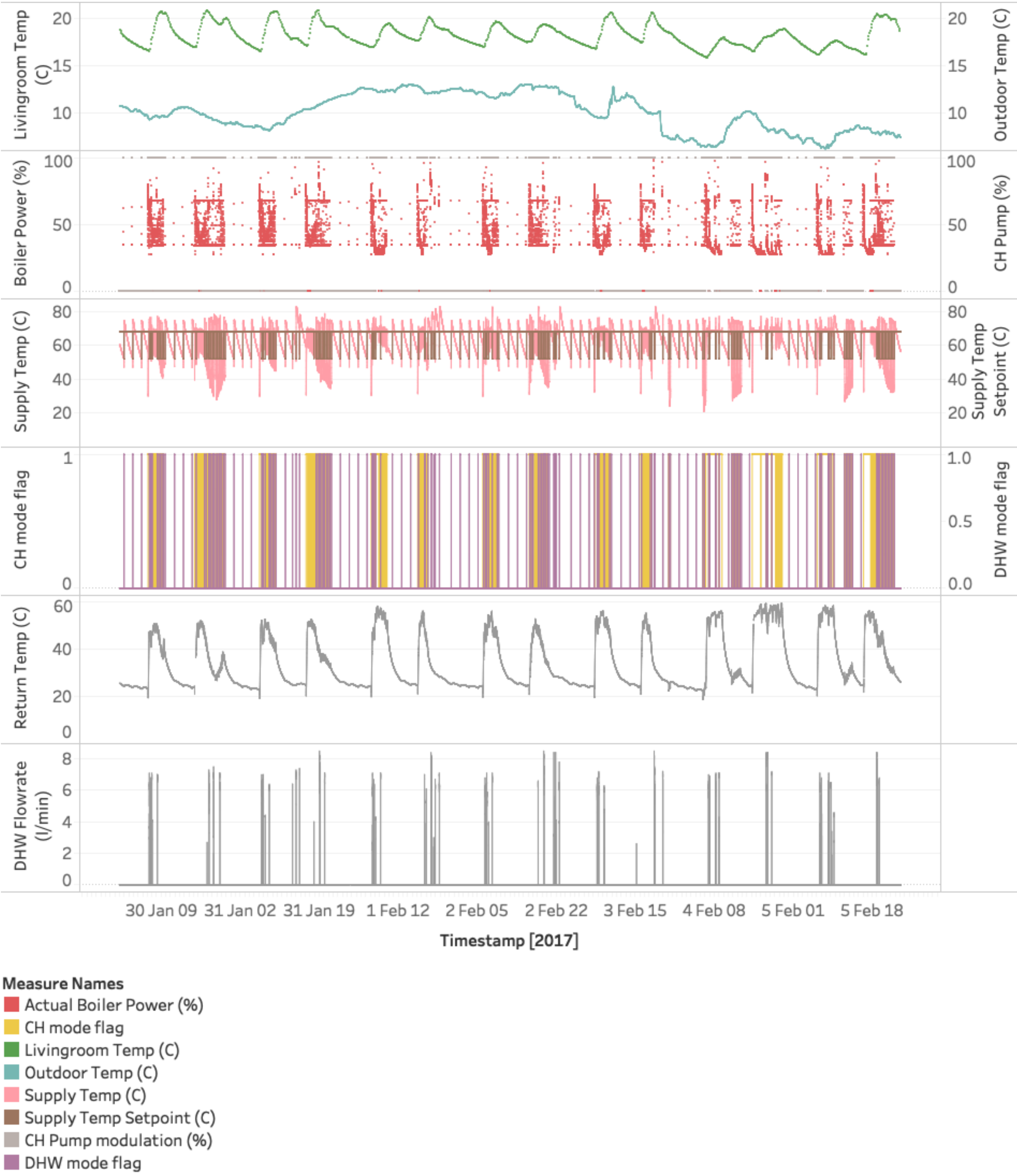


Figure 76: Building UK2 winter week profile (selected channels)

In UK2 a striking feature of the data shown in Figure 77 is the regular boiler firings outside of the heating schedule which are associated and flagged as DHW operations. These seem to be occurring at regular intervals (see 0000-0600) and are characterised by a short burner operation and associated rapid rise in supply temperature, but no DHW flow rate, i.e. no hot water demand by the occupants. At first this may seem like an unexpected user behaviour but since no actual hot water flow is present then these burner operations are more accurately categorised as 'keep-hot' or 'comfort' operations. This functionality is unique to combi boilers but is algorithmically and, in terms of objective, similar to the control strategy of a hot water storage tank system. Although combi boilers' operating principle is that of 'on demand' instantaneous heating of hot water, they are not without thermal mass and appliance heat loss. The thermal mass of the heat exchanger (commonly a plate heat exchanger, PHE) and internal water content can lead to a delay in the delivery of hot water if everything starts at room temperature. Keep-hot functions were developed to maintain the PHE above a certain temperature in order to compensate for this delay. If the CH supply temperature drops below a given value, then the 3-way valve switched to DHW mode, the burner fires and hot CH water is circulated through the PHE until the desired temperature is reached.

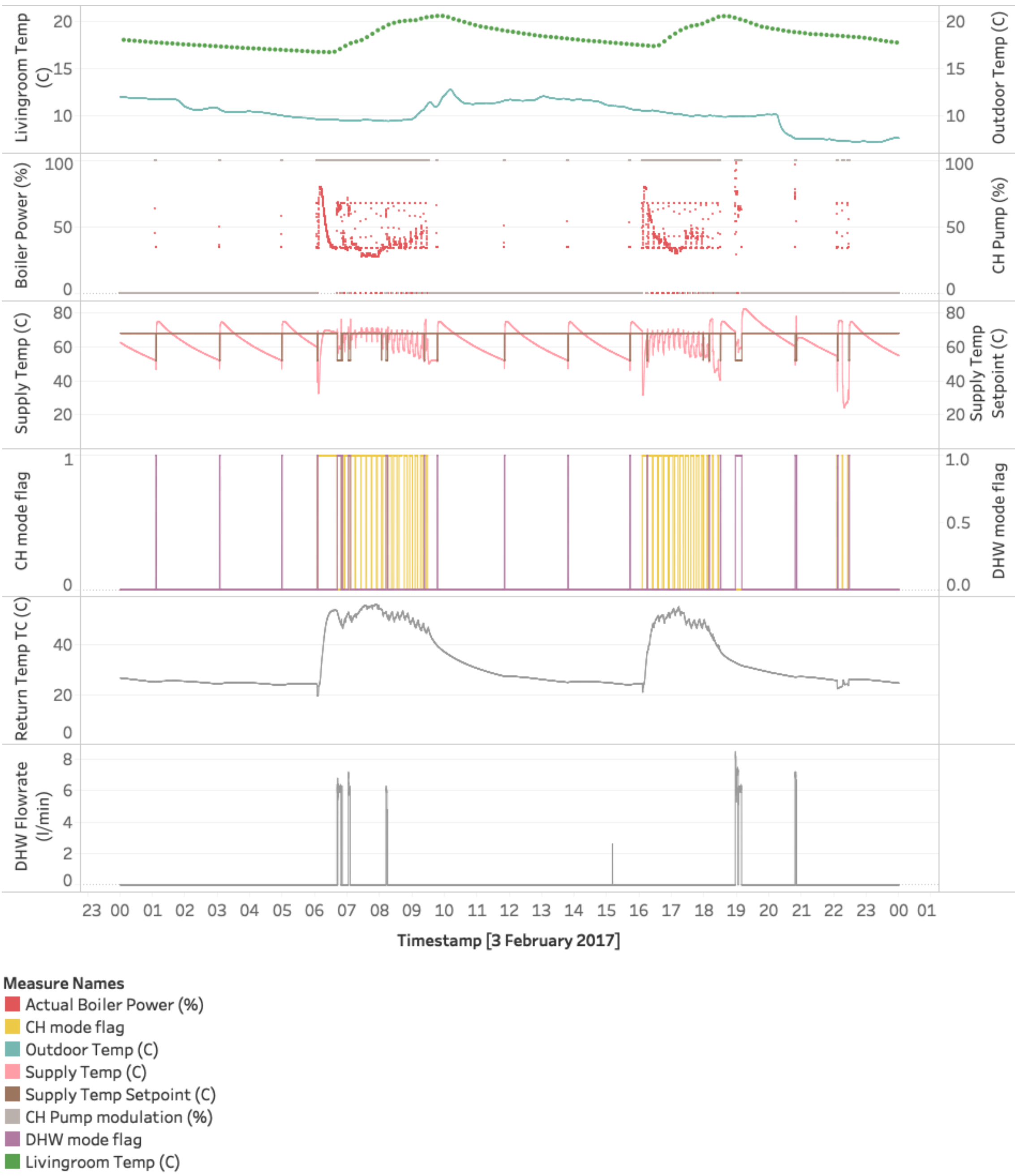


Figure 77: Building UK2 winter day profile (selected channels)

From Figure 78 it can be seen that in this case the CH temperature at the start of the keep-hot operation was at 52°C, at which point the DHW mode flag is set to 1, the pump is activated and 10 seconds later the burner is running and the supply temperature is raised during the burner operation, lasting 40 seconds, to just over 73°C. The burner is switched off just prior to this higher temperature level being reached but the pump continues to run throughout, for a total of 1minute and 20 seconds.

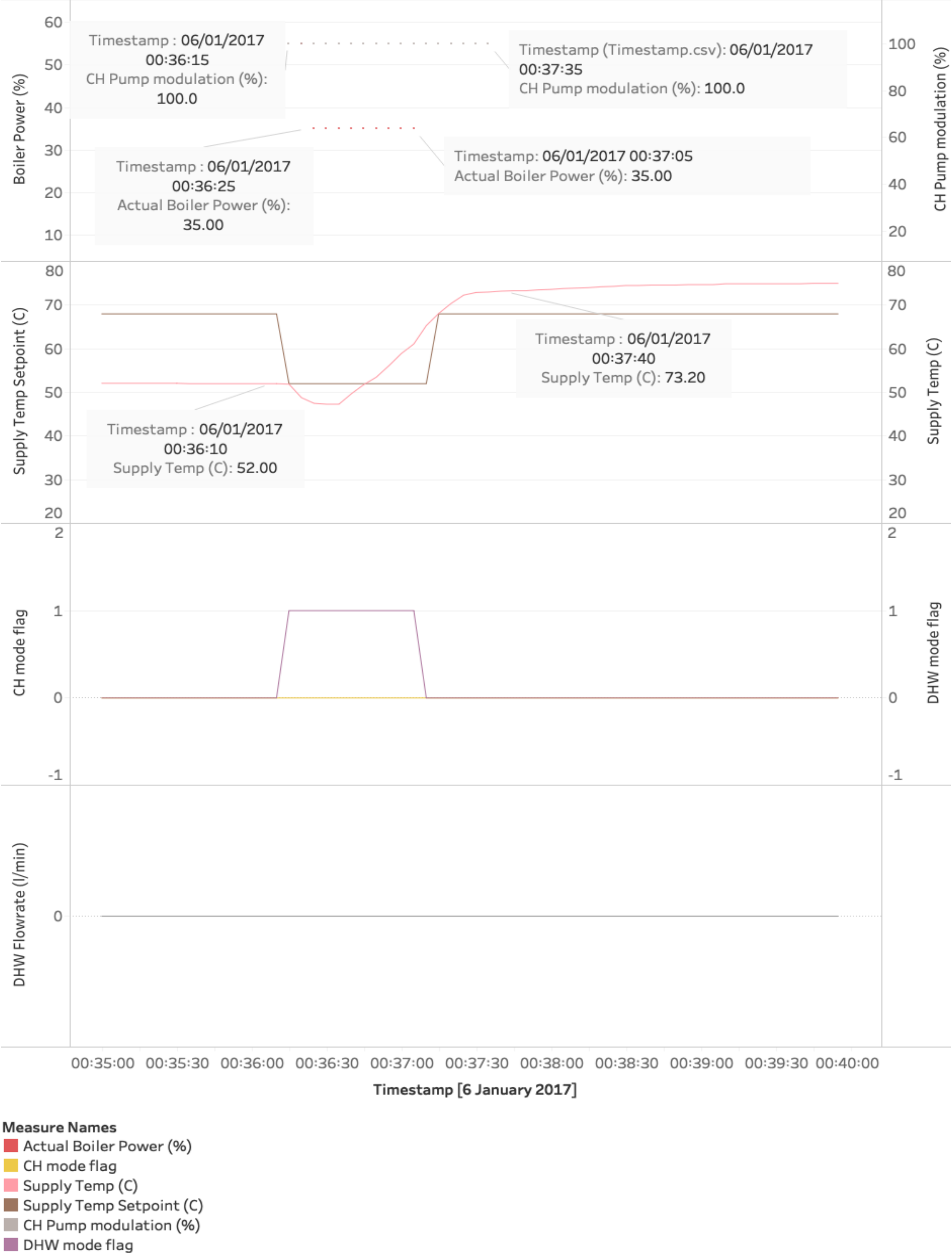


Figure 78: 'Keep-hot' operation in detail

As can be seen from Figure 79, the time taken for this stored heat in the PHE and appliance internal water to dissipate and the supply temperature measurement to trigger another 'keep-hot' operation is approximately 1 hour 50 minutes.

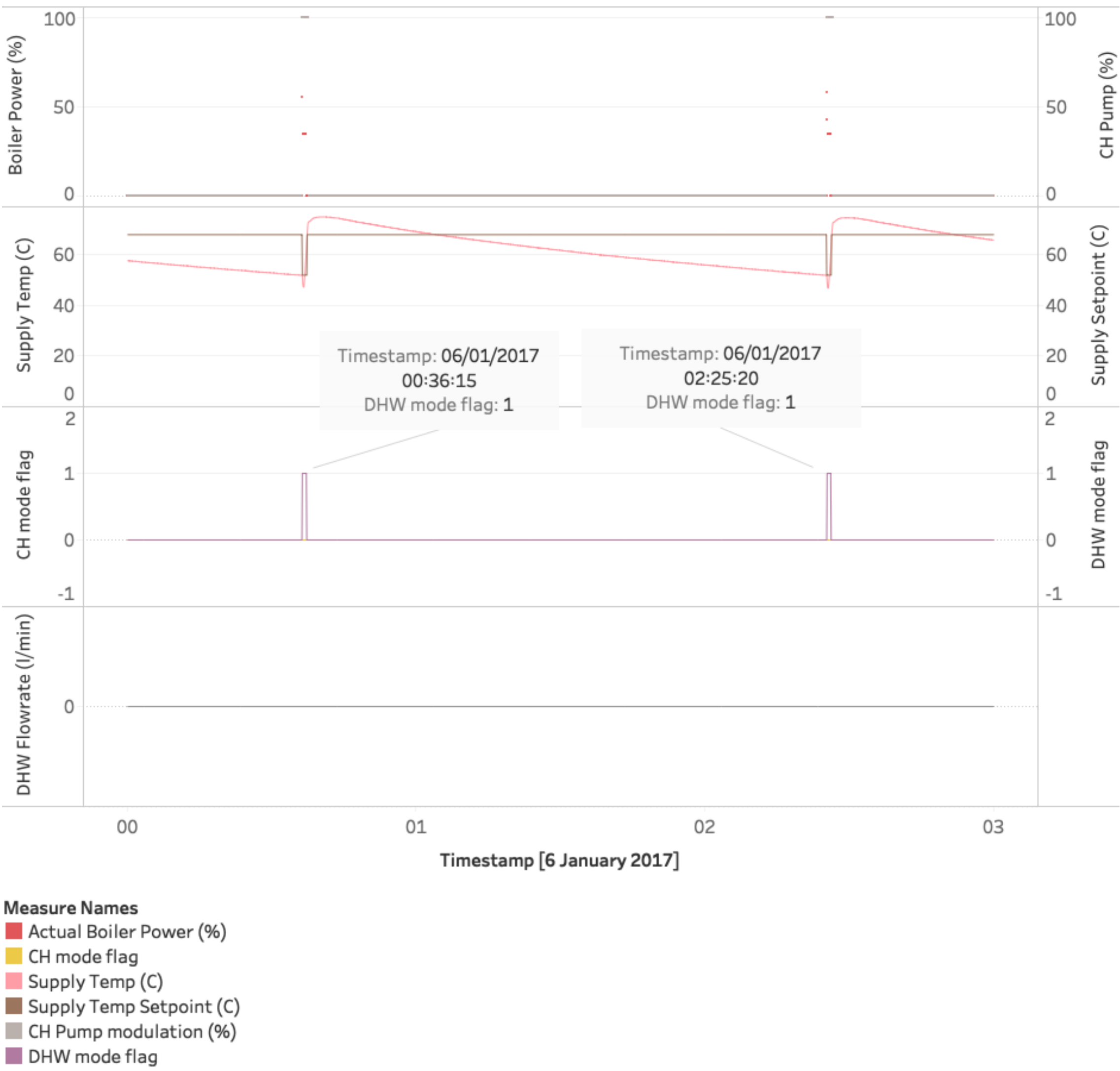


Figure 79: Two consecutive 'keep-hot' functions

Looking more closely at the data recorded in the morning, the CH heating profile is similar to that of UK1, with the recognisable cycles occurring once a relatively steady state room temperature has been reached. The cycling, as in UK1, points to a saturation of the available heat output capacity through the current heat load being less than the modulation of the boiler, closing of TRVs or under capacity of the radiators. Already the latter can be seen to be contributory with approximately 11 kW of emitter capacity available for the 24kW CH output boiler. What occurs when a hot water demand is made during the programmed heating schedule can also be seen. Since DHW always has priority over CH operation, then space heating is suspended while the DHW demand is satisfied. In Figure 80, three hot water demands are recorded. The flow turbine signal in the bottom trace indicates the measured cold-water flowrate entering the boiler which triggers the demand and also informs the boiler of the initial power level that should be required to heat that flow of water to the setpoint temperature. Once the flow rate has been identified and the DHW Flag activated, then the CH heating would be interrupted (burner and pump stopped) (if active), the 3-way valve would be switched to divert the supply water to the internal circuit and PHE, and the setpoint of the water reduced to the level required to give the desired hot water temperature (settable on the boiler interface).

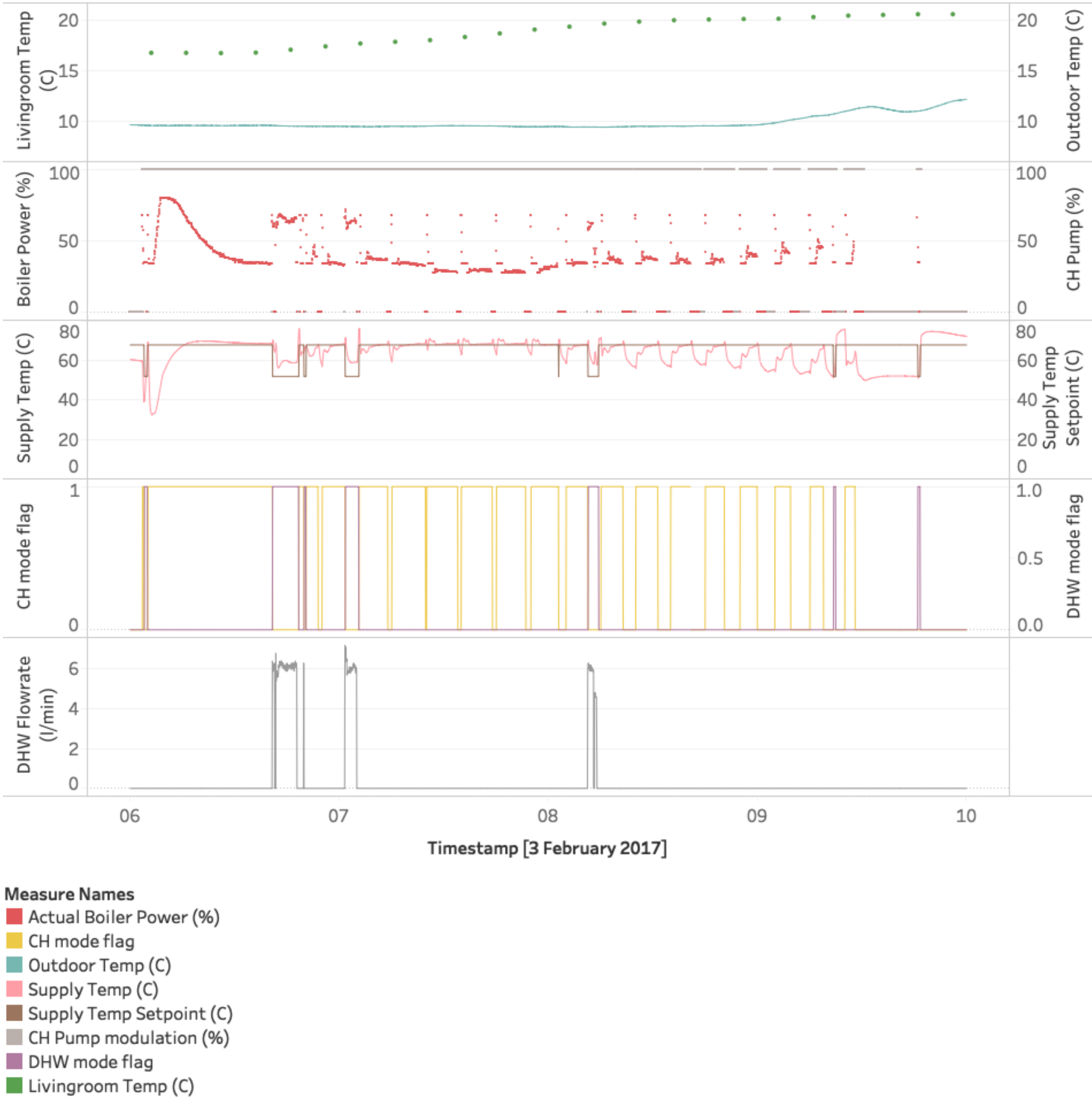


Figure 80: Building UK2 winter morning profile (selected channels)

6.1.3 UK3 day profile

Building UK3 has a quite different heating system from both UK1 and UK2, most notably the boiler is not a combi, meaning the boiler does not heat the domestic water in the appliance but via a separate hot water tank. Although one might expect the boiler rating to be lower since instant hot water is no longer required, the installed boiler has an output range of 7-27kW making the upper end of the modulation range (as with UK 1 and 2) oversized compared to the 12.6kW of radiator capacity. Also, significantly different is the control system, in this case a Worcester Wave controller (Bosch, 2018a), whereas the controllers in UK1 and UK2 gave simple binary signals to the boiler to request heat, the controller in UK3 attempts to deliver an appropriate power signal level depending on the temperature gap to be bridged and the current outdoor temperature. This configuration of controller, with outdoor sensor, puts it in ErP Class VI ‘Weather Compensation’, resulting in an additional 4% heating system efficiency gain when considered in SAP and EPC calculations.

The heating system had additional solar thermal panels fitted to the roof of the property and connected to a storage cylinder with corresponding additional measurement channels of collector temperature, tank temperature and solar pump operation. These additional measurements can be seen at the base of Figure 81. In terms of heating system analysis, the different structure of UK3’s heating and hot water system has the consequence that the DHW energy demand cannot be directly derived from the boiler power levels, the intermediate storage tank means that direct DHW demand, in form of flowrate and duration is not available since the DHW does not flow through the boiler. No flow sensor is installed, or necessary for operation since DHW demand can be indirectly determined by a drop in storage tank temperature, whether this occurs by static heat loss, or the drawing of hot water subsequently replaced by cold water, is of no importance to the boiler functionality. When the boiler fires it is possible to deduce which demand type is calling for heat by means of the position of the diverter valve which is controlled, and logged, by the boiler and, as in a combi appliance, directs the supply water to either the space heating circuit or, in this case, the hot water cylinder heating coil. However, the diverter valve is always in one position or the other (CH or DHW), so the position signal does not describe whether the boiler is delivering heat, only when combined with the boiler power signal can the heat delivery be characterised.

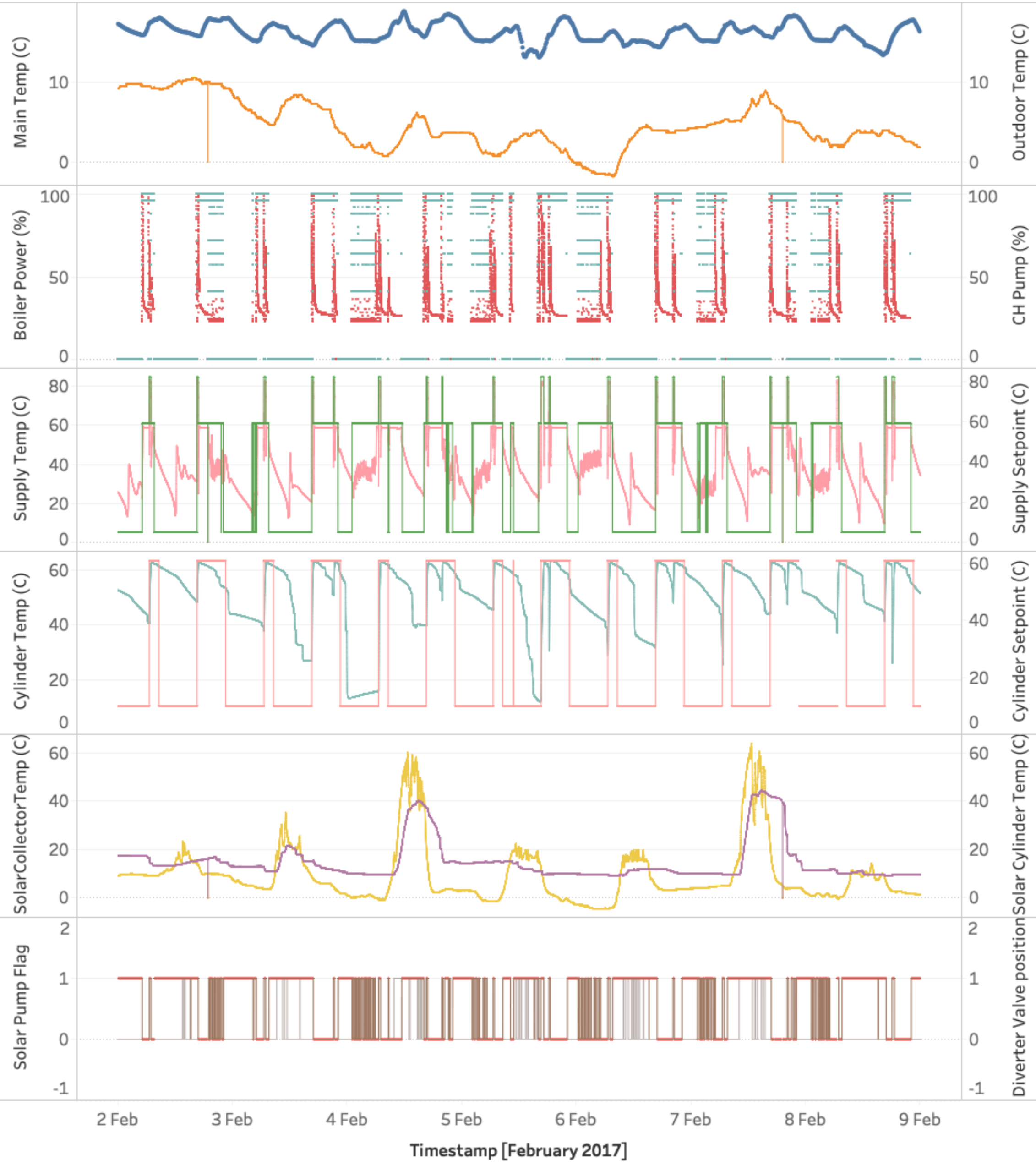


Figure 81: Building UK3 winter week profile (selected channels)

An efficiency benefit, as suggested by the ErP rating of the controller, would seem to be well justified when looking at the smoother control of power rate and flow temperature in UK3. The modulation range of the boiler allows the control to reduce the power input in line with losses for a given outdoor temperature so a benefit should be gained, so long as the hydraulic system does not present an alternative throttling mechanism by way of emitter sizes or radiator valves. Looking in detail at the progression of temperature and boiler state throughout the day highlights the way in which the difference in heating system specification manifest themselves in thermal response and dynamic behaviour. The boiler modulation level differentiates itself from that in the combis of UK1 and UK2, as there is no different upper limit for the CH and DHW power delivery, 100% (27kW). However, as with UK1 and UK2 the minimum modulation is restricted, in this case to 23% (6.5kW). The boiler control does distinguish, as was done in the combi boilers, between DHW and CH demand by the temperature of the CH supply water it is programmed to deliver. The supply setpoint level can change along with the diverter valve position giving a secondary confirmation of the demand type and boiler activity since when no demand is present the signalled setpoint is zero degrees Celsius.

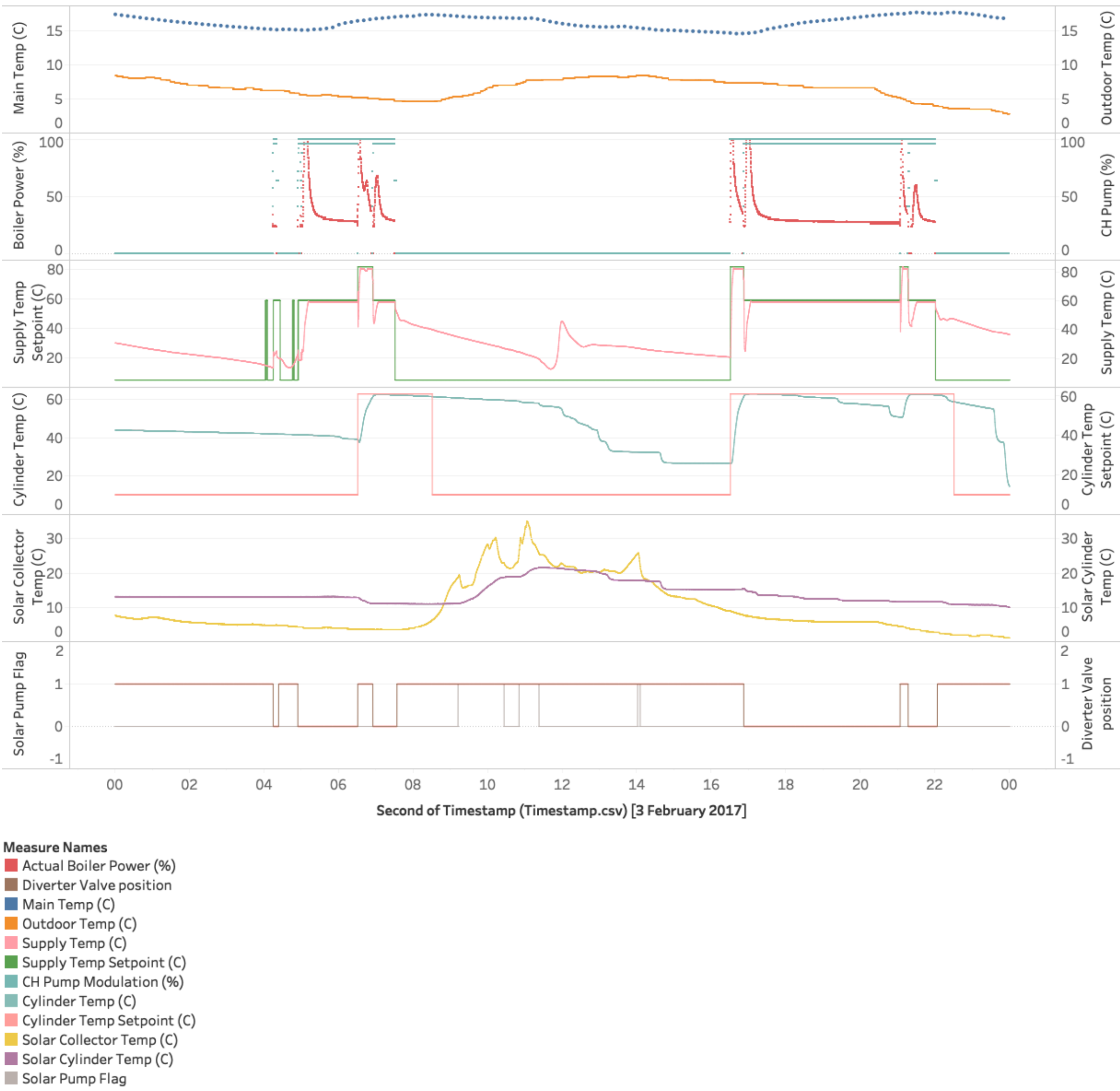


Figure 82: Building UK3 day profile (selected channels)

Looking at the data presented in Figure 82, in particular the boiler power in the second from top trace shows a clearer picture of heating operation with markedly less cycling compared to UK1 and UK2. The distinctive heating periods of morning and evening can be seen and how the boiler modulates to track current heat demand and temperature difference from internal to external. In between the two heating periods there can be seen a peak of solar collector temperature (second from bottom) and an intriguing event at midday effecting the supply temperature measurement which undergoes a short dip and rise before continuing its inter-heating decline. This event was seen on a number of days and is, as yet, unexplained despite discussions with the homeowner himself, but it could be a gravity current caused by the higher solar panel temperature compared to the supply temperature.

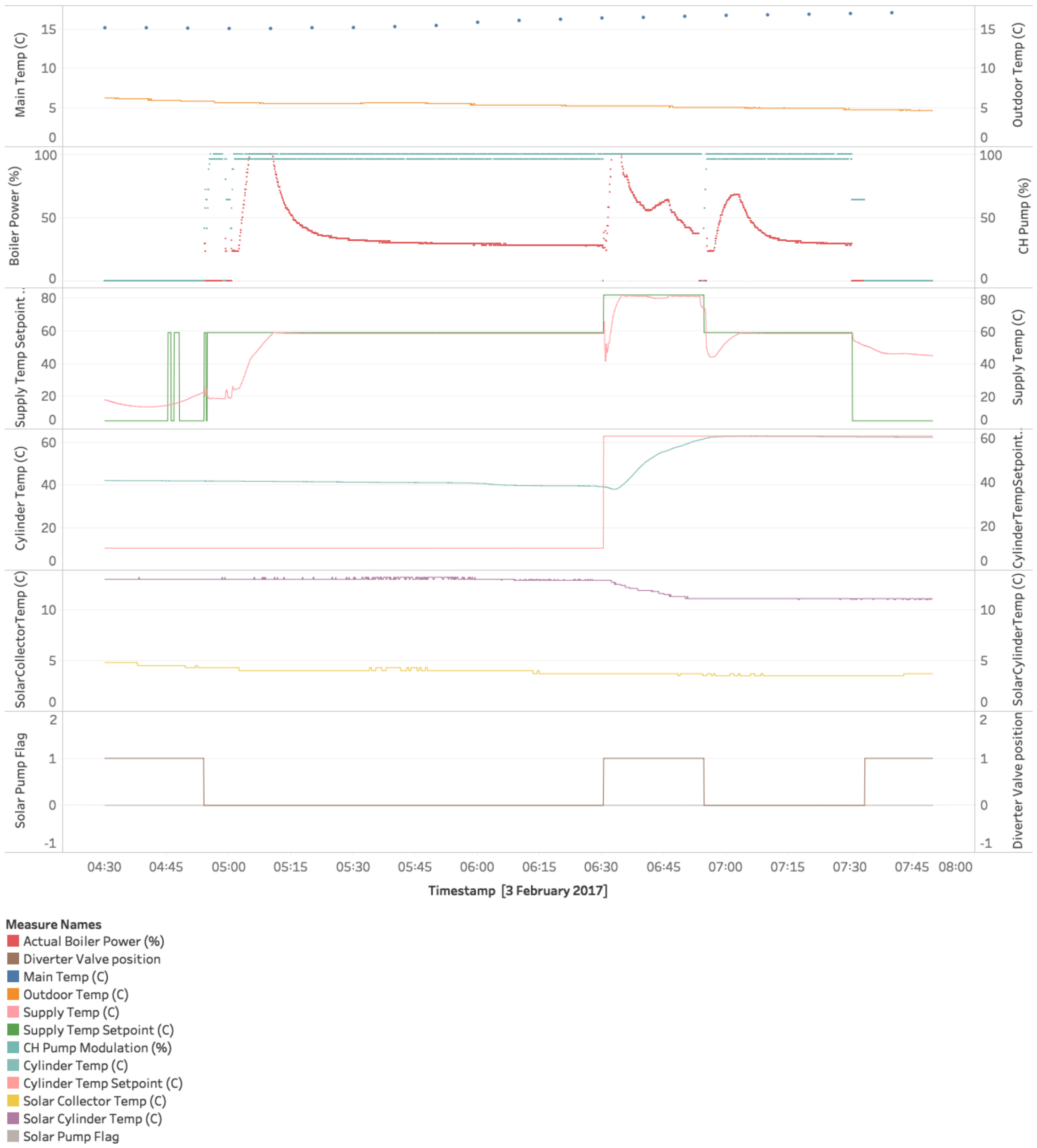


Figure 83: Building UK3 winter morning profile (selected channels)

Figure 83 shows only the morning heating period in order to analyse the modulation, cycling and CH/DHW switching in more detail. Regarding the operating mode (CH or DHW) from the lowermost trace, the diverter valve position can be seen, where 0 corresponds to CH and 1 to DHW. From 0500, CH mode is active but it seems that at the start of this heating period, the room/outside temperature relationship is such that the controller sends only a brief signal to the boiler calling for heat, followed by a period of inactivity forced by the anti-cycle function, but as the outside temperature continues to drop the power signal is increased and a period of uninterrupted heating continues until 0630 when a hot water demand (note the change in diverter valve position) begins along with the associated increase in supply setpoint temperature, until the cylinder setpoint temperature is reached, after which CH operation can continue.

That the CH operations last for over 1 hour, compared to minutes in UK1 and UK2, can be explained by looking at two differences to the other case studies: the improved control methodology of the room thermostat and the lower modulation level of the boiler itself. The controller is capable of sending a more information-rich signal to the boiler than a simple ON/OFF, this allows the boiler to modulate gradually down as the setpoints for room and supply temperature are approached, avoiding overshoots which could trigger other internal algorithms leading to burner termination. That the minimum modulation can be maintained for such a duration may be explained by the lower thermal output of the boiler, allowing a temporary thermal equilibrium to be reached, although to better understand this, the heat loss of the building should be known in conjunction with the already measured internal/external temperatures. A deeper analysis of the building heat loss will be carried out in section 6.1.5 and 6.1.6 to assess the relative sizing of the boiler and therefore the suitability of the boiler in terms of thermal output.

6.1.4 DE1 day profile

With DE1, the analysis moves from the UK to a residence in the surroundings of Stuttgart in southern Germany. As was seen at the beginning of this chapter from the monthly averages of outdoor temperature, the summer and winter temperatures were slightly more extreme than those in the UK, especially in January 2017 and the summer of 2016. The heating system in DE1 is broadly similar to that in UK3, without combi functionality, but with storage tanks and solar thermal panels. The room controller is also the more sophisticated modulating type, again with outdoor temperature measurement for weather compensation. DE1 does possess some unique features beyond the location of the building. The installed boiler was a new model from Bosch with a larger modulation range of 1:10 compared to the more traditional and widespread gas boiler modulation range of 1:5 or 1:6, and was also equipped with an inbuilt return temperature sensor (Bosch, 2017a). The property had a secondary heat source, a 5kW wood burning stove in the living room, which had no direct measurements to record its use, although the occupants reported infrequent use of this heat source. The heating schedule differs from all the UK based houses under observation; in DE1, the 24-hour daily heating schedule is defined by just 2 temperature levels and 2 heating periods, a daily heating scheme and a night time setback period. This is in line with accepted practice, as represented in the German NCM (DIN, 2011a).

From Figure 84 one can see the different heating schedule in action, with seven clearly defined daily blocks of boiler activity over the week period.

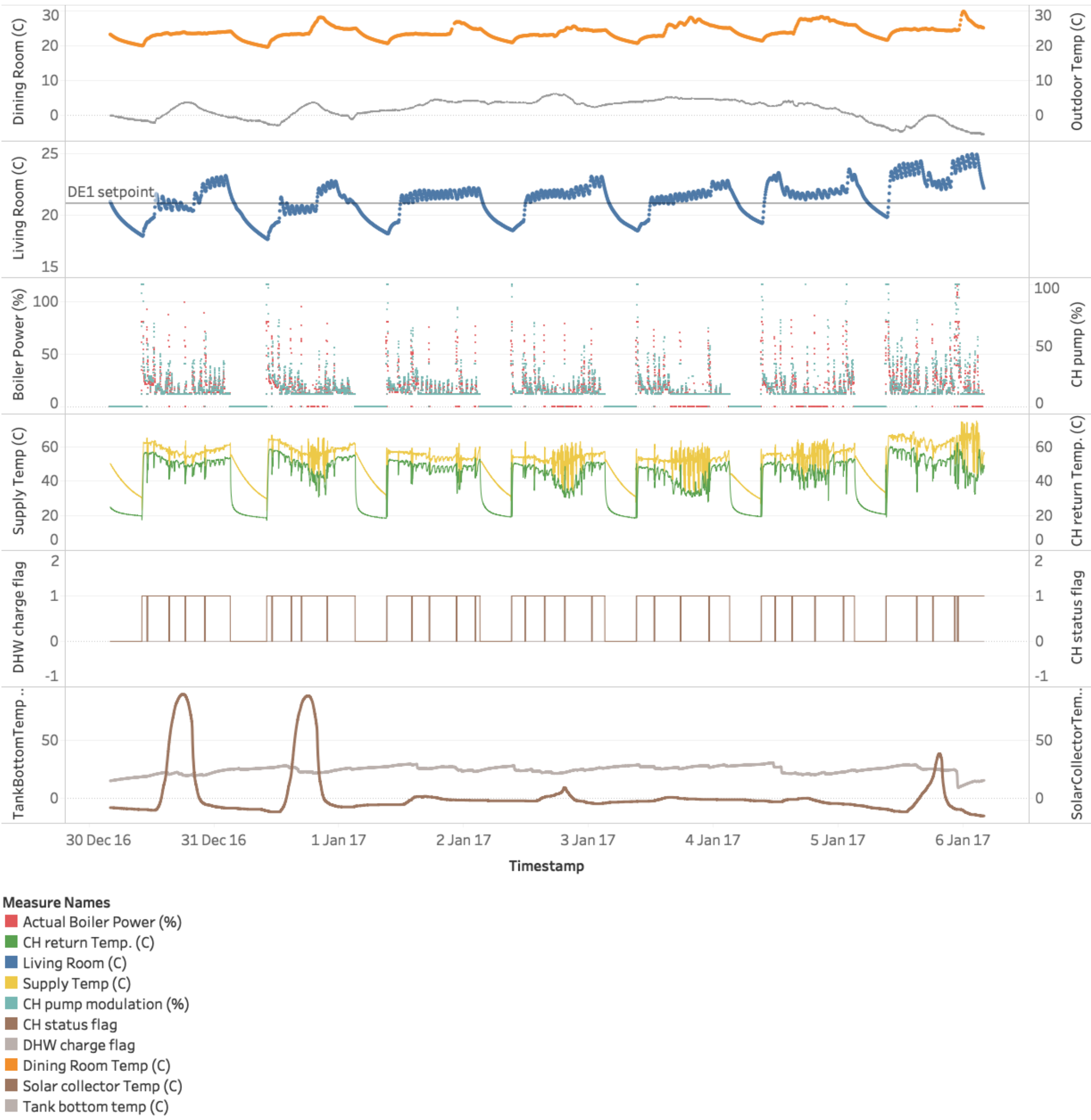


Figure 84: Building DE1 winter week profile (selected channels)

Looking more closely at the day schedule in Figure 85 it is evident that from 0500 until the end of the day the boiler is mainly active in CH mode, as seen from the generally non-zero boiler actual power level and the CH status flag value of 1. The measured temperature in the living room is consistently above the reported setpoint during this daytime heating period indicating possible measurement offset error in that room location or the influence of the secondary heating system during the colder days at the end of this week. The temperature reacts concurrently with increases in CH power throughout the day as the boiler oscillates between near minimum modulation of 15% and mid-range of 40%, which gives the impression of an effective feedback control system. Boiler power is modulated but the supply temperature, and importantly, its offset to the return temperature, remains relatively constant with an approximate difference of 10°C. At 1900 a period of DHW heating, following the drop in tank temperature, takes place with higher levels of boiler power output, after which the boiler seems to enter a phase of cycling similar to that of the UK buildings, but in this case the CH pump runs almost continuously throughout. This period of more intermittent boiler operation creates a less stable supply temperature, and the occurrences of near overlap of supply and return temperatures are indicative of the lower level of heat transfer to the building.

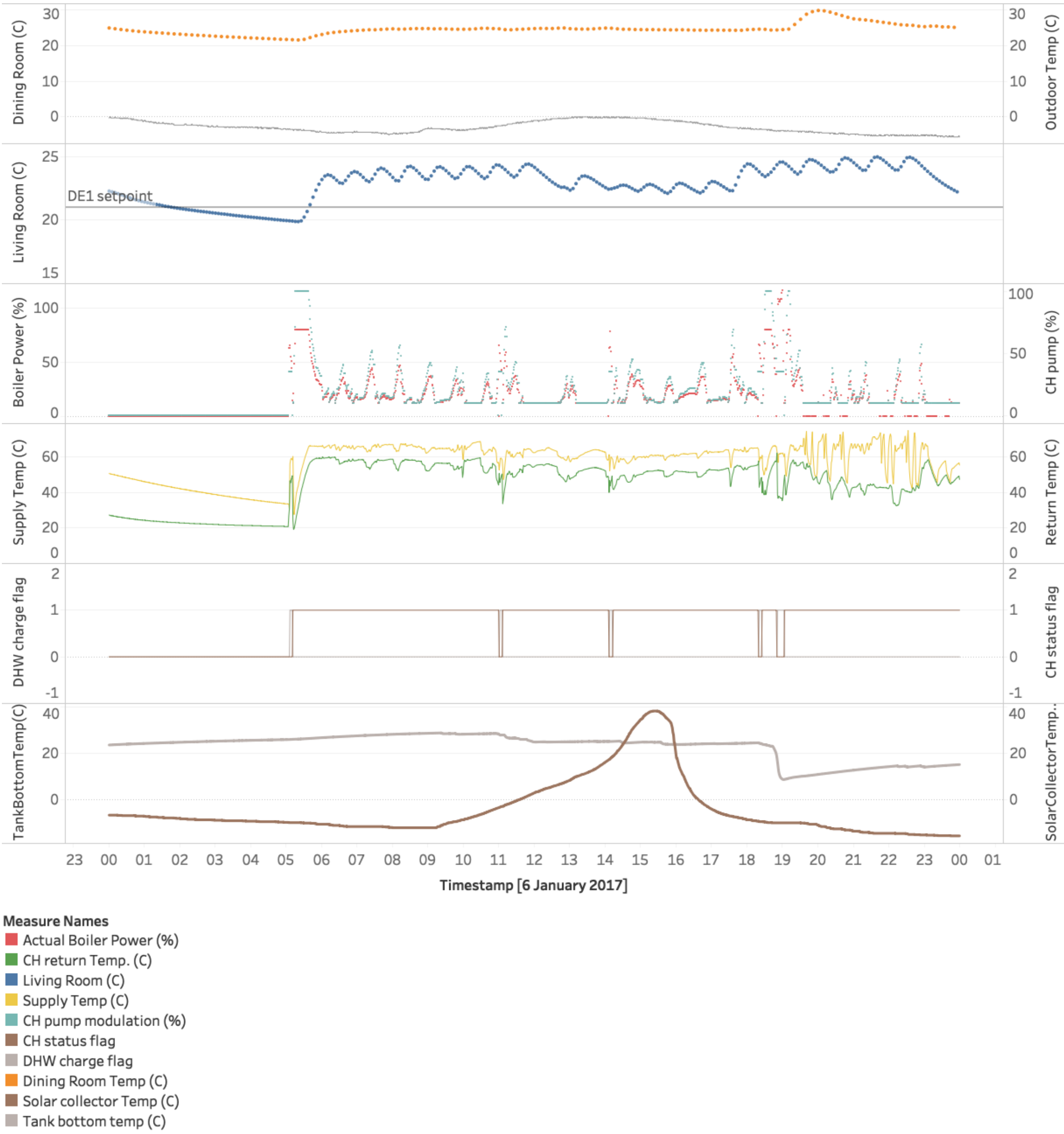


Figure 85: Building DE1 winter day profile

Figure 86, shows a short 5-minute DHW tank heating period in the early morning which delays the CH schedule to later than the programmed 0500, but after that a familiar high load (80%, max CH load) for over half an hour to bring the room temperature and supply temperature to their setpoints, after which the modulating power and pump levels maintain the constant operation.

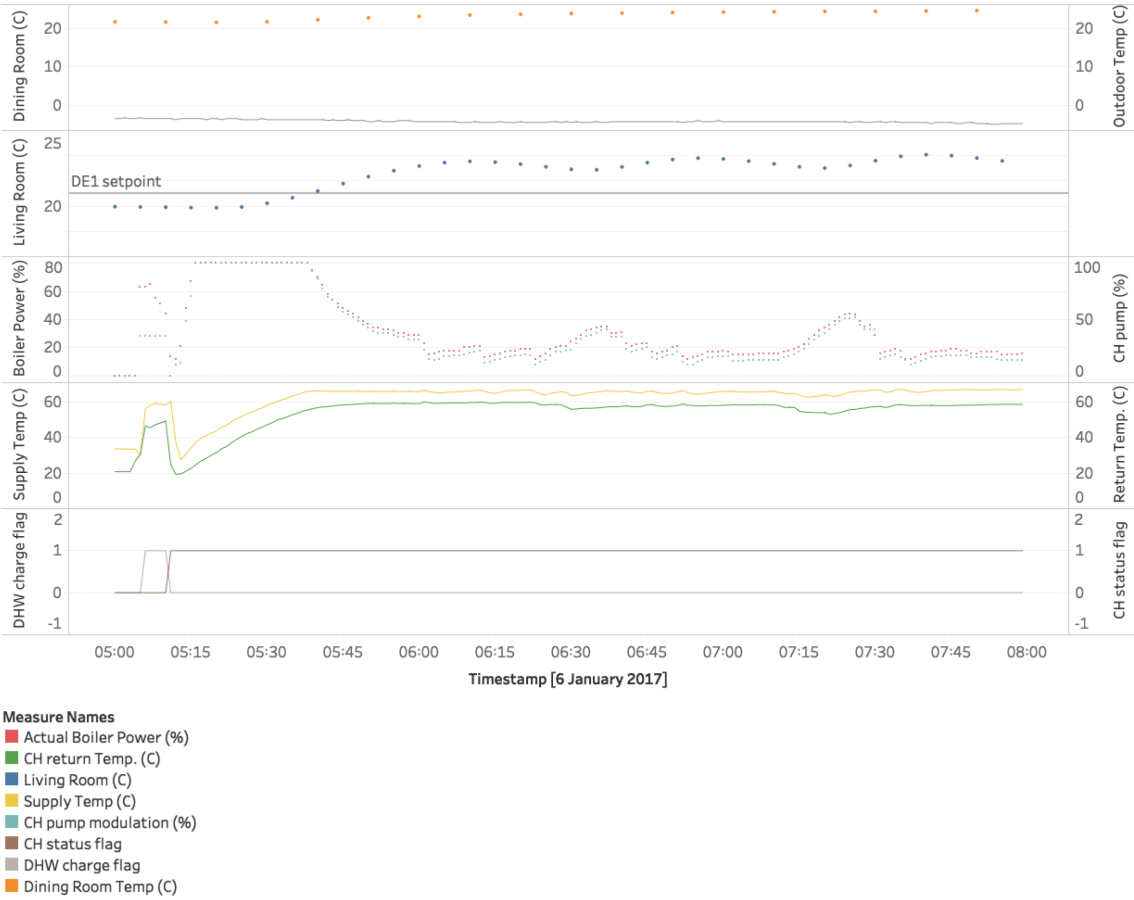


Figure 86: Building DE1 winter morning profile

6.1.5 Boiler & Plant size ratio

At the heart of this thesis is an analysis of the dynamic behaviour of heating systems as they operate in buildings, with a view to understanding and enabling their optimum usage. However, the building fabric and how it contributes to the heat loss is a critical part of the building energy system. During the collection of field data for empirical Dataset A, the assessment of the total building heat loss was desirable to understand not only the context of the buildings themselves and whether they could be legitimately categorised as high or low heat loss properties as seen from their EPCs, but also to investigate using the new data source from the heating appliance to address aspects of the HLC measurement process which have previously been highlighted as problematic (Stamp, 2015). Through the process of analysing the data with the goal of building heat loss calculation, should open up the possibility of automated HLC determination from connected boilers or heating appliances with modern controls, thereby improving EPC quality and allowing cost effective in-situ validation of building fabric retrofit interventions. In this case, after quantifying the building heat loss of the buildings under observation then a deeper analysis of the boiler behaviour in the context of the installation building can be performed, supported by plant size ratio assessments.

6.1.5.1 Steady state heating test

In building UK1 a short steady state heating test was carried out while the building was still occupied. The occupants agreed to set the thermostat setting to constant 22°C for a 28hour period between 12:00 14/01/2017 and 15:00 15/01/2017. This is less than even the minimum 72hr advised duration for a co-heating test from the literature (Stamp, 2015), but given the restriction of occupancy and cooperation from the residents this was the only workable compromise available, with the benefit that the building would already be at a reasonable steady state temperature before commencing the trial. This experience illustrates some of the practical difficulty of performing traditional co-heating tests in real buildings once occupied.

As seen in the analysis of UK1 daily profile by selecting certain data channels different pictures of the heating system situation can be built up with time, in this case the three desirable parameters: CH heating power from the boiler, outdoor temperature and indoor temperature. Two additional sources of heat could be excluded from this short trial by selecting the measurement period of 2200-1200 because, in that period no solar (night time and a period of heavy cloud) or DHW gains were present. Clearly this is less than ideal due to the thermal mass effects over such a short period when wall temperatures will not necessarily be stabilised. The data, including solar radiation measurement is shown in Figure 87.

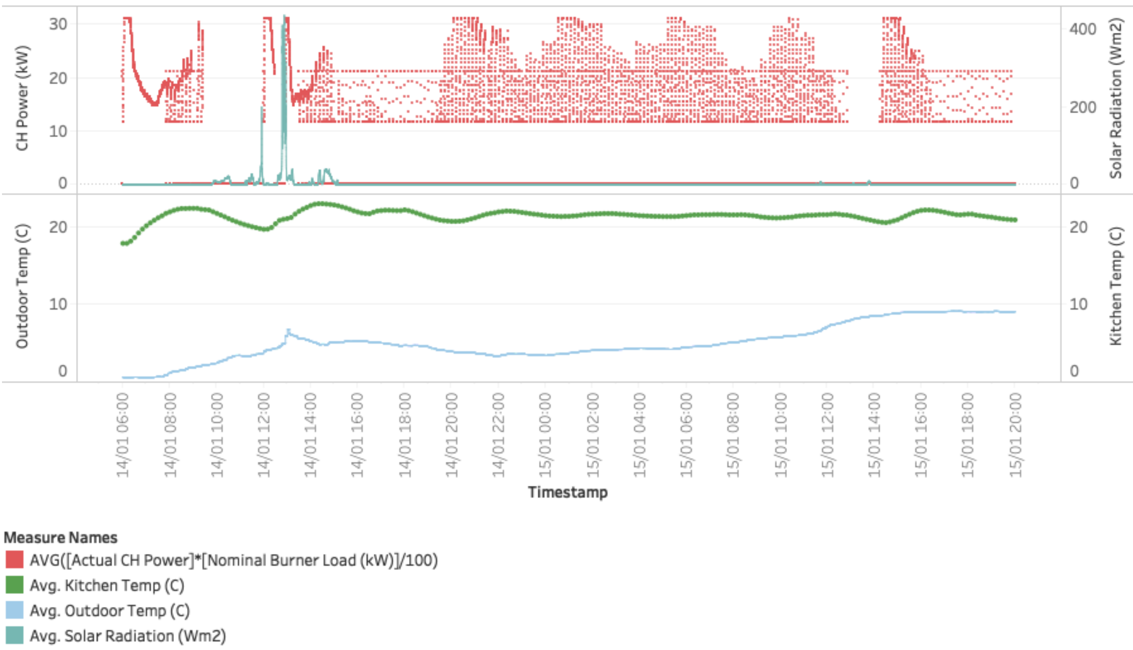


Figure 87: UK1 Co-heating test data, Boiler Power, Solar, External/Internal for building

With this data an hourly heat loss can be calculated using the internal/external temperature difference and CH boiler heat input, assuming that steady state had been reached and no significant additional heat sources were active.

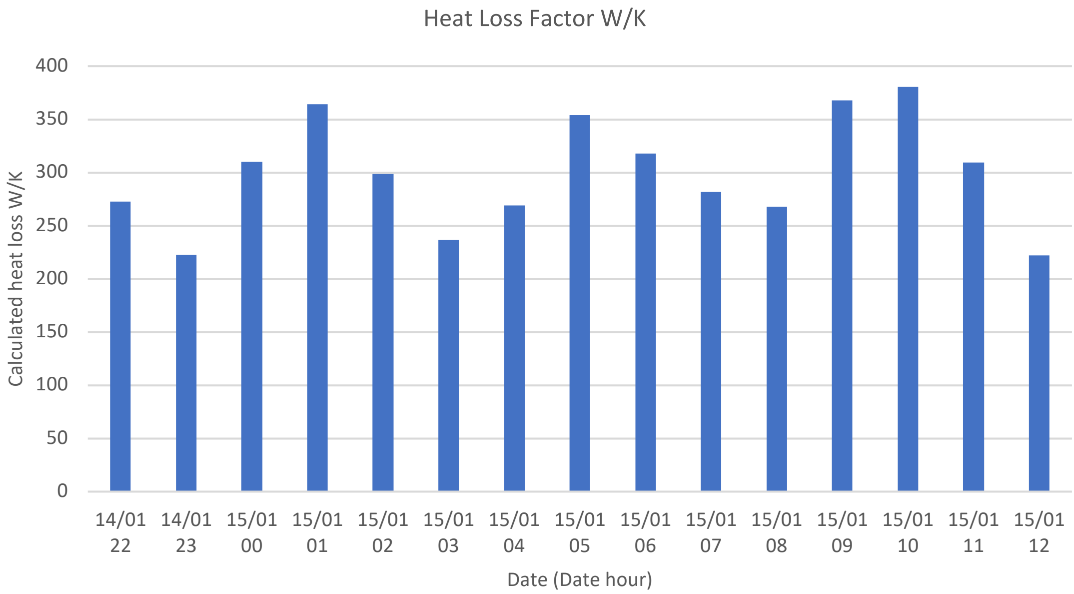


Figure 88: Hourly calculated heat loss of UK1 14/01/17 2200 until 15/01/17 1200

The resulting hourly heat loss values are shown in Figure 88, where the mean is 298W/K. As can be seen from Figure 87, which includes the pre- and post-measurement data, the indoor temperature oscillated for some hours after the period started at 1400; from 2200 onwards, the indoor temperature remains stable and the solar radiation has naturally reduced to zero, conditions which are maintained throughout the night and into the following morning.

This attempt to conduct a steady state heating test in an occupied house was not only disturbing to the occupants themselves both in terms of disturbing the normal heating schedule and perceived financial cost, but the results are subject to significant uncertainty due to the compromises made to achieve even this limited result. Most notably the short duration of the test and the inability to accurately account for user generated internal gains. As such, and because of the potential benefits of a new type of measurement, a derivation of building heat loss from the boiler EMS diagnostic data was attempted.

6.1.6 Power Temperature Gradient (PTG) from boiler power data

A co-heating test, or the steady state heating test attempted in the previous section, should be a truly steady state test, or at least as far as it can be with the variability of solar, wind and other meteorological conditions. This is often not a practical method of measurement when buildings are occupied, as is the case with the buildings under observation for this thesis. It should be possible to use the heating system data itself, while the building is in use, to estimate a heat loss coefficient. This being more cost effective due to using existing measurement infrastructure from within the heating system itself.

Given the short period over which a co-heating test could be carried out in this case and that the building was occupied throughout, a secondary method of estimation of the building thermal loss was carried out. Namely that of the Power Temperature Gradient (section 2.4.1). Since the necessary data (energy consumption and internal/external delta Temperature) was available for a period of many months, then a calculation could be carried out using measurements from a longer period than co-heating tests. Additionally, if there is a good correlation between the results using measured gas consumption and that from the boiler power derived consumption, then the method could be extended to the housing data where no detailed meter data was collected. If it proves possible to directly use boiler data then this could provide an alternative to smart meter data as a source for PTG and also a notable improvement, since boiler data has additional parameters allowing disaggregation between boiler operation for heating and hot water, potentially providing a novel heat loss calculation method for EPCs and smart building control systems.

In order to justify using boiler diagnostic data for use in the Power Temperature Gradient, one must first be sure that reported gas consumption from the boiler is of comparable accuracy to gas meter measurements. Therefore, it is necessary to assess the correlation of boiler data derived gas consumption with the measured gas consumption at the building gas meter. In the cases of UK1 and UK2 buildings, additional Loop optical sensors had been placed on the gas meter giving a direct transcription of the displayed meter reading and consumed kWh of gas every hour. For the comparison with the boiler data, two channel types from the EMS data stream are utilised together with one global boiler parameter. For all types of boiler, the ‘Actual Boiler Power’ is used, which reports the current reported boiler power level as a percentage of the maximum. To reiterate here, the boiler power level is an interpreted variable derived by the boiler in parallel with the fan speed in premix gas boilers (the majority boiler in the UK market). The pneumatic operating principle of such boilers means that the under pressure created by the fan controls the flow rate and accuracy of gas flow from the pneumatic gas valve (SIT, 2018), therefore there are good grounds to believe that the boiler power level data is a good proxy for gas consumption.

Although it should be possible to compare the hourly values from the gas meter and the boiler, consideration should be given to the way in which the two methods operate. The boiler reports the instantaneous boiler power, whereas the gas meter acts as an integrator, summing the gas used over the previous timestep. This could be compensated for in the calculation of the used energy on an hourly basis, but a timeframe of 1 day was chosen for the assessment of correlation as well as the further steps concerning the Power Temperature Gradient where temperature variation also plays an important role.

$$\sum_{day} Gas \approx \sum_{day} Aux + 24 * BoilerMax * \overline{ActualBoilerPower_{day}}$$

Equation 13: Equating measured gas consumption to appliance consumption

Where Gas= hourly measured gas consumption in kWh

BoilerMax= reported Boiler maximum output in kW

ActualBoilerPower = percentage of maximum power, averaged over chosen time period

Aux = auxiliary gas consuming appliances e.g. cooker, gas fire excluding hot water from the boiler

The equation above shows the method for calculating the plotted boiler gas consumption. From the daily average boiler power, a percentage value must be multiplied by the scaling factor of the specified boiler output in kW. As can be seen in Figure 89, the correlation between the two data sources of boiler and gas meter energy logging gives a good linear correlation, meaning that not only is the boiler accurately reporting the power and therefore energy demand, but that the auxiliary gas consumption seems to be insignificant in the case of UK1. Although the relationship is not one to one (gradient=0.98, R^2=0.983), the gas meter readings are 3.2% less than the boiler readings according to the linear regression. The intercept on the y axis indicates that the boiler is not the only gas consuming appliance on the premises, a gas oven is also present which could account for the approx. 1.5kWh of gas consumed per day not accounted for by the boiler. One significant outlier data point can be seen, one with higher than expected gas meter measurement, corresponding to measurements on 24th of November when the weblogger went partially offline.

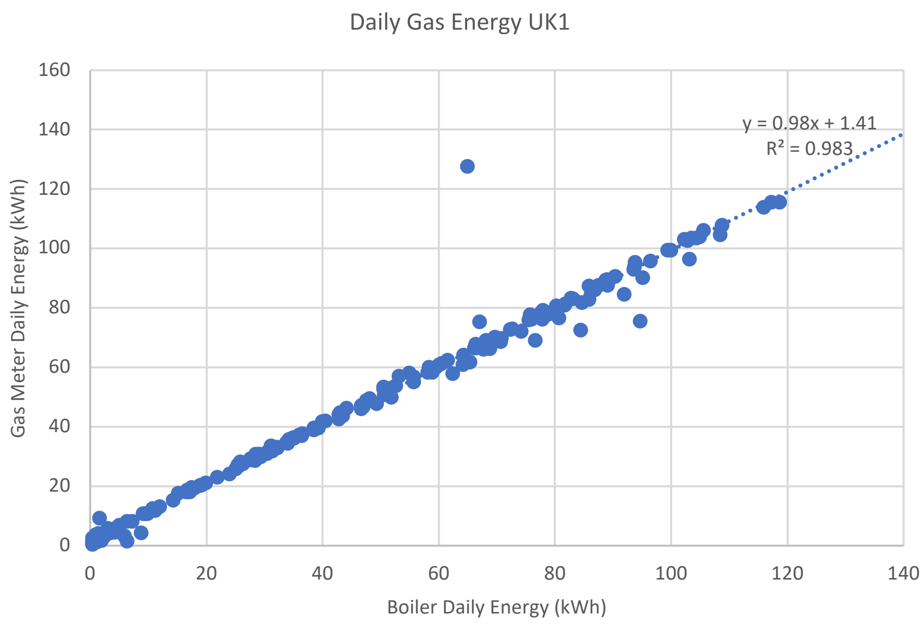


Figure 89: Correlation of Boiler measure energy against gas meter measured energy UK1 Building

UK2 also shows a good correlation with the notable difference of a larger zero offset of 8.24kWh due to a collection of data points of less than 20kWh where the consumed gas outstripped that derived from the boiler consumption. This may be an issue with the data collection of related to the higher occupancy compared to UK1 (young family of 4, retired couple), the cooking gains from UK2 are a possible cause as there are no other gas consuming appliances in the house. Again, one data point jumps out as an outlier, although, this time there is no interruption in data recording on that day on the 21st of March 2017, leaving the conclusion that there was some sort of communication or sensing problem which led to the discrepancy.

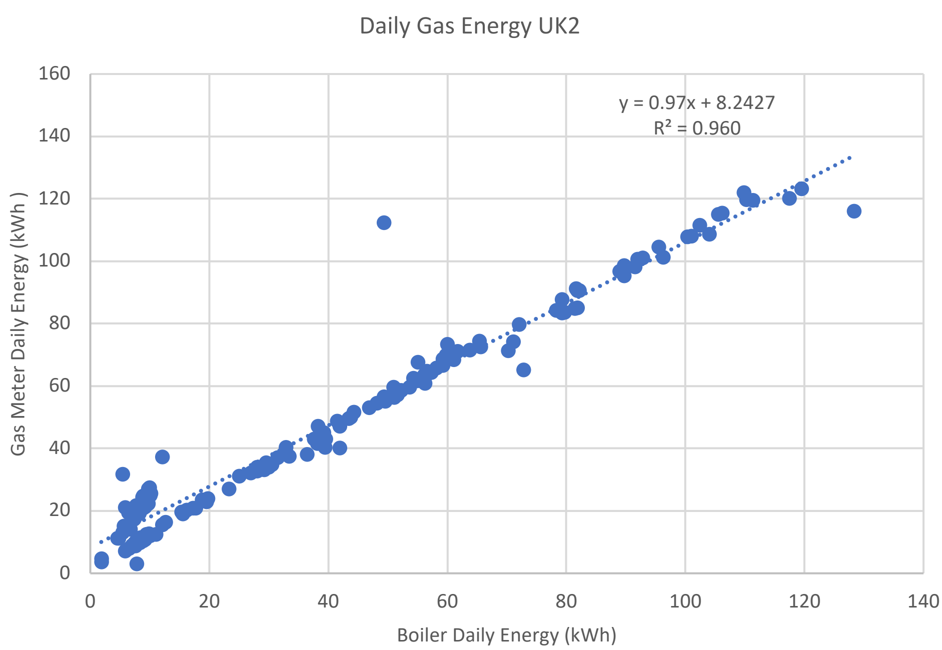


Figure 90: Correlation of Boiler measure energy against gas meter measured energy UK2 Building

To compare boiler derived energy consumption with the gross gas meter readings then it is sensible to take the total boiler power. However, a significant advantage of taking the boiler data direct from the boiler control EMS system is the ability to disaggregate between CH and DHW power.

To disaggregate when the boiler was operating in CH or DHW mode it is necessary to follow the methodology used to previously display the individual house data, starting by distinguishing between combi and system boilers. Practically this means whether the diverter valve which sends the heated water to one or other circuit is internal or external to the boiler. As noted in section 4.3.2, in the case of combi boilers, not only is the instantaneous boiler power reported, but also 2 flags indicating the boiler operation mode. These flags were used to filter the boiler power channel prior to averaging or aggregating steps, and give only CH or only DHW operation. In the case of non-combi boilers this method can also be followed, but instead of the flag channels (which effectively indicate the position of the internal diverter valve), the external diverter valve channel can be used instead. By doing this, the power data can be disaggregated and Power Temperature Gradients based only on central heating power can be derived.

$$\sum_{day} Gas_{heating} \approx 24 * BoilerMax * \overline{(ActualBoilerPower * \mathrm{CH}\ Flag)}_{hour}$$

Equation 14: Gas heating consumption balance

Where Flag= direct mode status as Boolean for Combi Boilers, 1 for CH mode, 1 for DHW mode. For other boilers, similar flag derived from Diverter valve Boolean channel could be used.

Heat produced by the boiler in CH mode and circulated round the building radiator network is not the only contribution the boiler has to space heating. DHW also flows through the building and collects temporarily in showers, baths and basins before leaving the building. It is recognised that this can contribute to space heating to the order of 25-40% (Uglow, 1981, DECC, 2012). The plots of boiler power against temperature difference are made for gross boiler power and CH only, the difference being DHW and DHW related operations such as ‘keep-hot’.

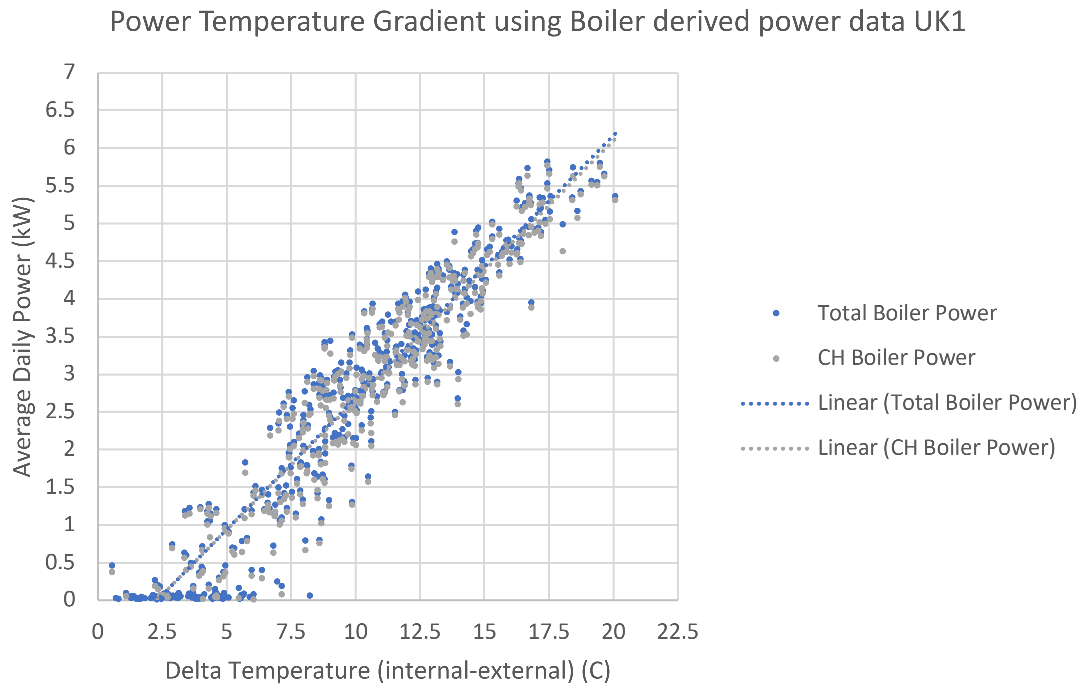


Figure 91: Power temperature gradient UK1 (Total boiler power, and boiler CH only, daily)

In Figure 91 the two sets of data from UK1 are shown: total boiler power on that day and CH boiler power, with the latter displaying fewer data points due to removing days with zero CH input during summer, but still DHW activity.

A specific feature of UK1 was that, although the boiler was a combination boiler, the most frequently used bathroom in the house was equipped with an electric shower and the house is occupied by one retired couple, resulting in a proportion of boiler operation for DHW which is low compared to the other dwellings under observation and larger studies. Weekly hot water consumption from the boiler was between 100 and 150 litres with some peaks corresponding to reported visitors using the second bathroom. This would place the house very much at the lower end (lowest 5 %) of the observed range according the EST survey (EST, 2008), but this excludes the hot water from the electric shower. No disaggregation of the electricity consumption was possible, only the gross building demand, as measured by the Loop sensor, subject to the inaccuracies from inductive/resistive load issues. As such, the linear regressions shown for both sets of data for UK1 are closely related, with DHW playing only a small role. In both cases estimated building heat loss was around 340W/K. Seeing the data plotted in this format also alludes to the potential boiler size required for this building, with the mean daily heat power required over the measurement period not going above 6kW. More detailed linear regressions (one per building) will be shown after examining the four houses individually.

UK2, however, has a weaker correlation which could be related to the following differences to UK1

- Conservatory/solar gains
- Higher DHW usage
- Clothes drying with electric heater
- Family cooking/part-time working mother

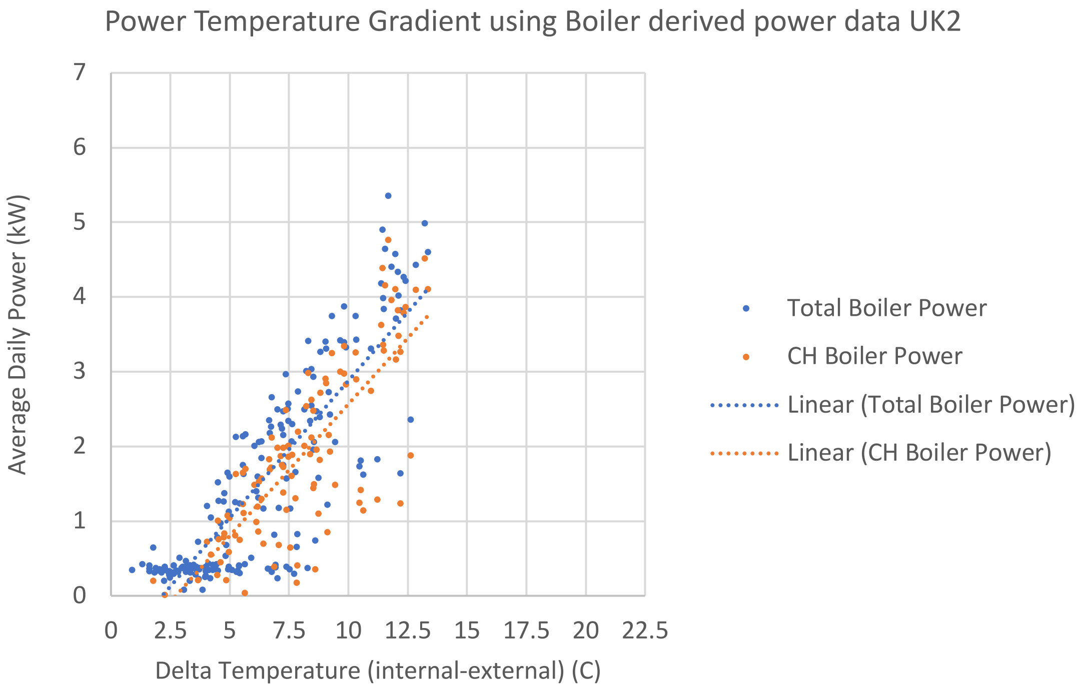


Figure 92: Power temperature gradient UK2, daily

With a shorter measurement period, data from UK2 covers a smaller range of temperatures than seen for UK1, giving a first estimate of around 350W/K heat loss but UK2, with a higher hot water consumption and therefore larger discrepancy between total gas consumption and that utilised for central heating, shows a weaker correlation than in UK1 with more scattered data points. A look at the effect of DHW boiler operation on room temperatures shows that in periods with no CH operation the local bathroom temperature will increase despite temperatures in other areas of the house (such as the kitchen), falling. Uglow (Uglow, 1981) used a 25% contribution of the DHW energy to heating and SAP assumes a 25% contribution from the gross DHW consumption plus 80% of the DHW distribution losses. In Figure 93 it is possible to see that bathroom temperature (second from top trace) increases by 1.5°C in the evening (8 Jan 20, corresponding to 2000 on 8th of Jan 2017) when DHW flow has been detected but no central heating (bottom trace); for comparison, the main living area is shown by the kitchen temperature. Again, the cycling behaviour in central heating operation is clear to see.

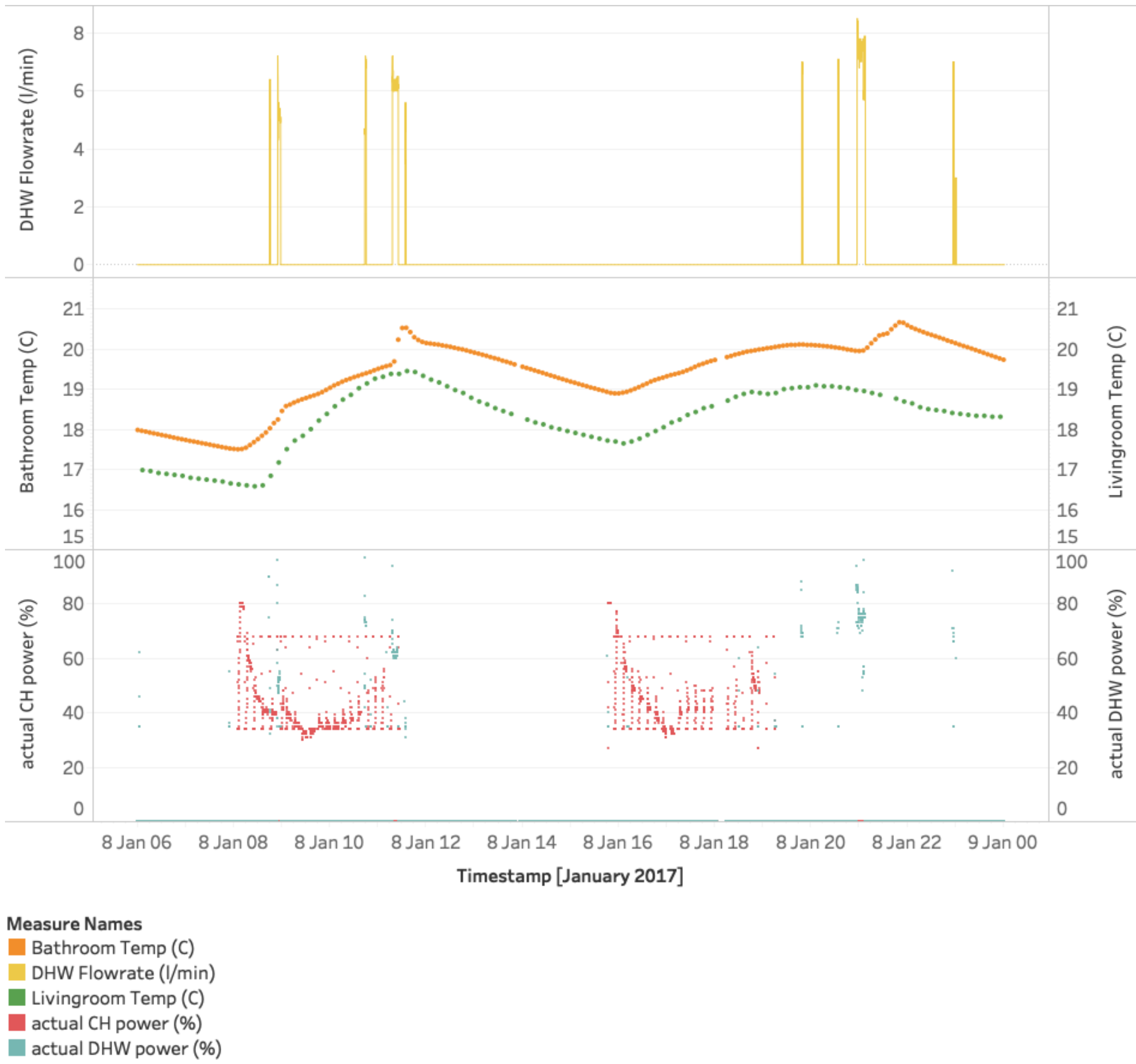


Figure 93: Influence of DHW on local room temperatures in UK2

The third UK house under observation differentiates itself significantly from the other 2 UK houses in terms of the domestic hot water heating. Not only is the hot water managed via a storage tank, additional thermal energy is fed in from the roof mounted solar thermal panels. In terms of PTG, this presents three pertinent differences in how the hot water thermal energy contributes to warming of the internal living space. In contrast to a combi appliance, where the hot water will be delivered almost instantaneously to one of the hot water outlets, most probably the bathroom, a storage system such as that in UK3 will provide a delay in the delivery, a division of the heat dissipated between the bathroom and the location of the tank (due to storage tank heat loss), and finally, the un-metered contribution of solar thermal. By stripping out the boiler power input destined for hot water heating (as indicated by the diverter valve position), the linear estimate for CH only is less steep relating to lower heat loss when disregarding DHW, implying a larger contribution of DHW either through distribution or tank losses.

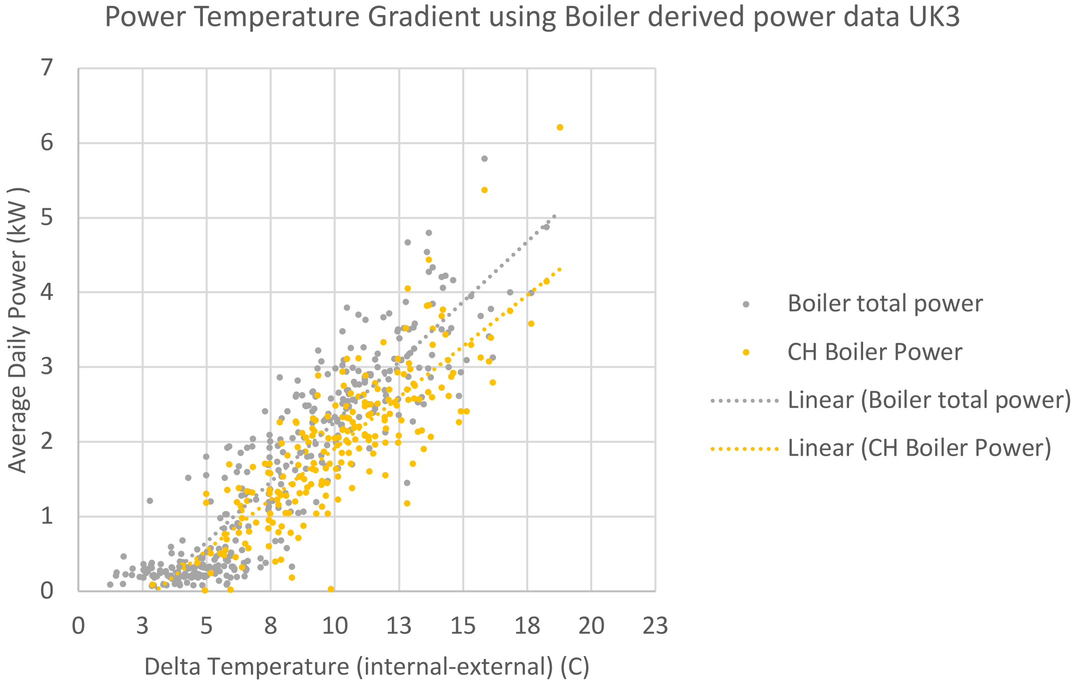
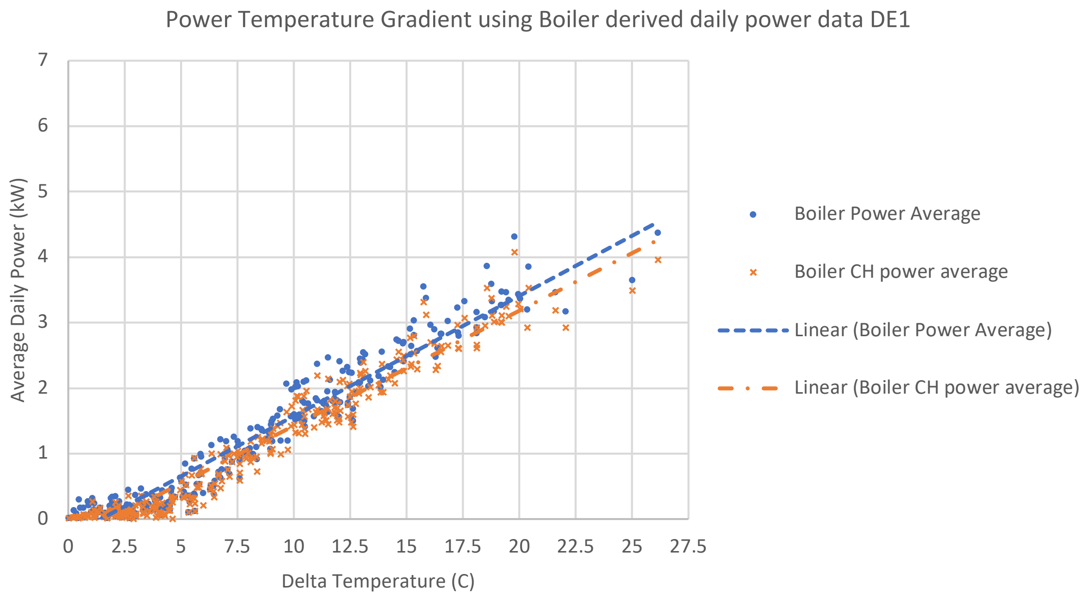


Figure 94: Power temperature gradient UK3, daily

DE1's data, as shown in Figure 95 shares a similarity to the heating system of UK3 but the smaller spread of data recordings between total and CH-only boiler power leads to the conclusion that the DHW losses are somewhat less. The overall lower scatter and lower maximum daily average power (max 4.5kW) could also be the result of more continuous heating and better insulation respectively, but there are a number of factors which could also be contributing, with a first estimate of 180W/K for total heat loss.



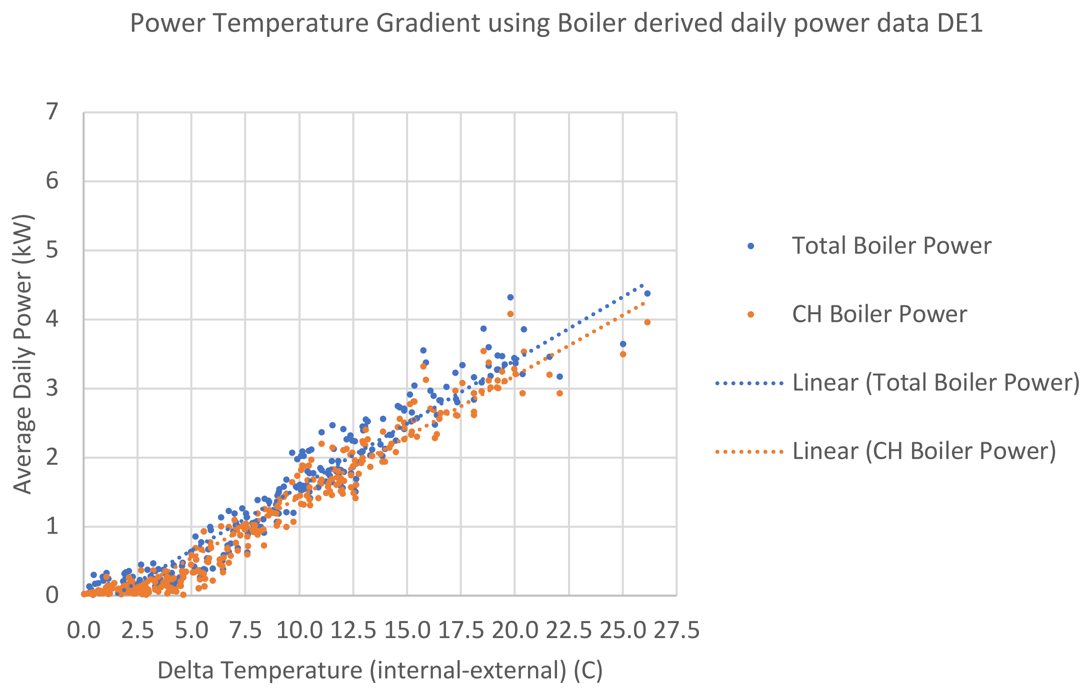


Figure 95: Power temperature gradient DE1, daily

The previous figures show that after disaggregating the CH and DHW daily power values, some uncertainty is introduced when the data is used to attempt a power temperature gradient assessment, due to the varying proportion of DHW demand in the different houses. In order to apply a standard process to all the data, and as a starting point for how such a process could be implemented in a standardised way in future, the following charts are plotted with a weighted assessment of the boiler power for days with space heating, where 100% of the CH power is considered, plus 25% of the DHW, which considers mainly the SAP methodology of DHW contribution to space heating.

The following figures replot the data from the previous charts but with this simple weighting of CH and DHW boiler heat input to the building. The resulting linear regressions are plotted, together with 95% confidence intervals. The linear regressions slope, b, is calculated in Excel (using the SLOPE function for linear regression), according to the following equation, and then plotted with the statistical 95% confidence intervals for the fitted regression line.

$$b = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sum(x-\bar{x})^2}$$

Equation 15: Least squares gradient

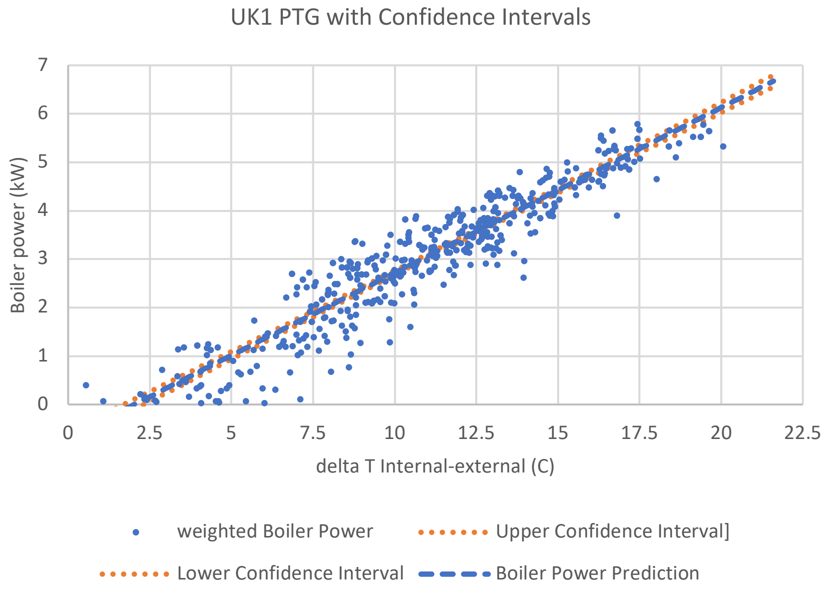


Figure 96: Power Temperature Gradient using Boiler derived power data UK1 with 95% CI

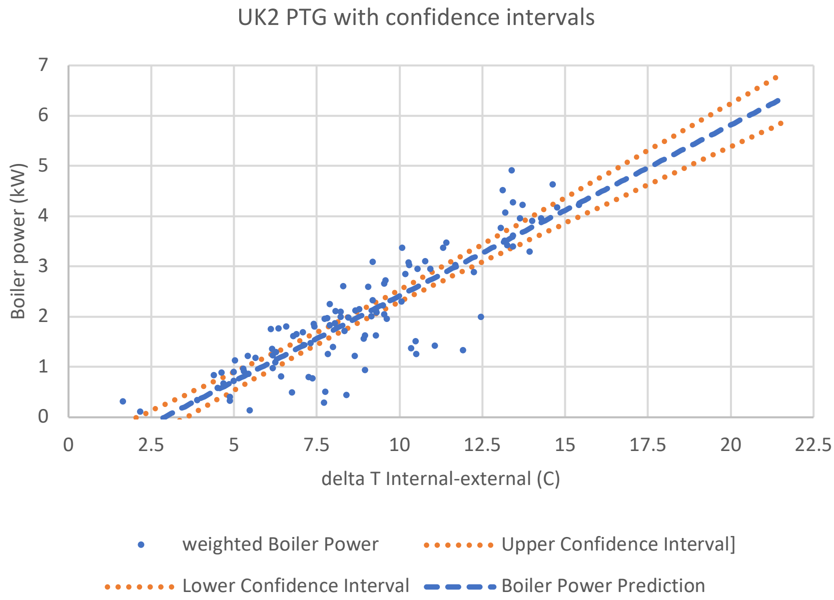


Figure 97: Power Temperature Gradient using Boiler derived power data UK2 with 95% CI

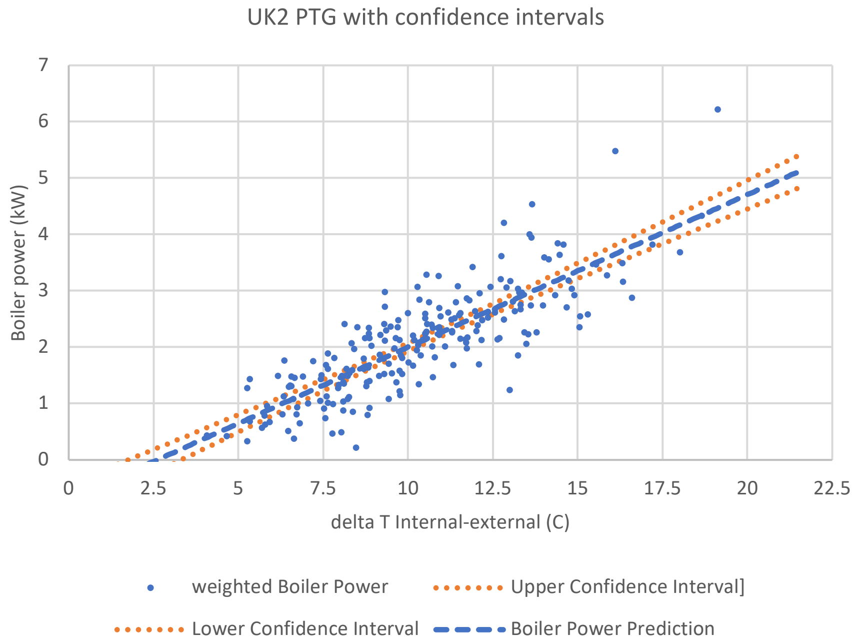


Figure 98: Power Temperature Gradient using Boiler derived power data UK3 with 95% CI

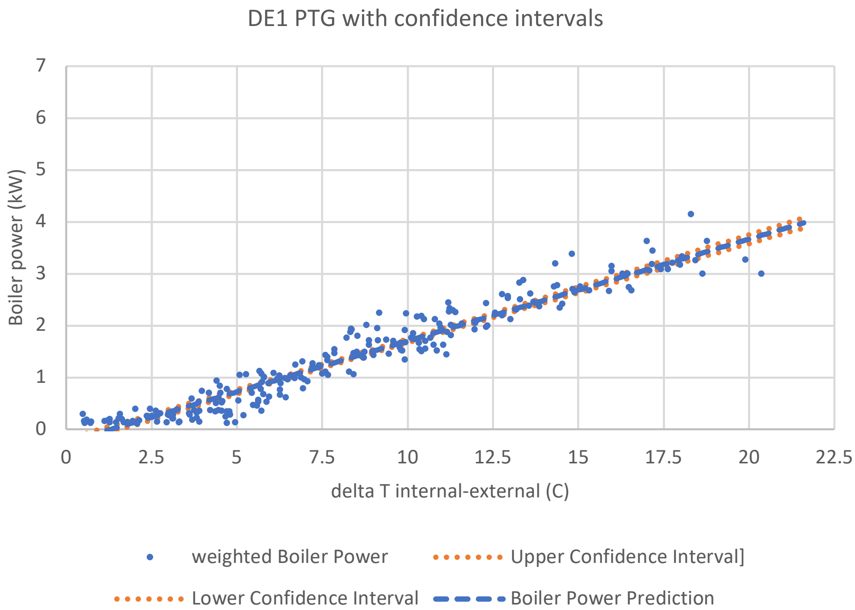


Figure 99: Power Temperature Gradient using Boiler derived power data DE1 with 95% CI

Summary of the regression parameters follow in Table 22, where the slope is shown, representing the PTG and the non-boiler gains which are defined as the y axis intercept of the CH only data, i.e. the apparent negative power needed to maintain a 0K temp difference internal/external.

Table 22: Table of PTG regression data

Calculation Values	UK1	UK2	UK3	DE1
Number of Samples	489	106	213	231
HLC (Slope of PTG) (W/K)	340.9	339.7	270.5	196.5
Y Intercept Non-Boiler Gains (W)	-691.3	-979.9	-705.2	-258.1
F Statistic	3.8606	3.9324	3.8859	3.8824
Pearson's R	0.9397	0.8712	0.8239	0.9654
R^2 Statistic	0.8824	0.7591	0.6788	0.9321

Table 23: PTG derived heat load and PSR comparison for boiler specification

	UK1	UK2	UK3	DE1
Design heat load (kW) (-5°C Ext 21°C Int.)	8.9	8.8	7.0	5.1
Radiator Capacity (kW)	21.9	11.3	12.6	-
Max Boiler CH power (kW)	31	24	27	25
Min Boiler CH power (kW)	8	7	7	2.5
PSR at max CH power	3.4	2.5	3.2	5.2
PSR at min CH power	0.9	0.8	1	0.5

(* Electric, solar and cooking)

Boiler power limits in CH mode are used above to calculate the plant size ratio at boiler minimum power, but from the observations in the houses it was measured that these values are not exact, and the observed minimum power levels encountered were somewhat different. The PSRs calculated on the observed boiler power levels are shown below. However, it seems clear that the boilers are all oversized compared to the building heat load under mid-winter conditions (-2°C external temp) and therefore may struggle to modulate down to the levels needed on milder days and the transition months. UK1 is the most oversized but all the UK boilers seem similarly oversized at their minimum modulation levels with the DE1 boiler appearing more accurately sized.

Table 24: PTG derived heat load and PSR comparison for boiler recorded power levels

	UK1	UK2	UK3	DE1
Min Boiler CH power (kW) (recorded)	11.8	7.5	6.2	3
PSR at min CH power	1.3	0.9	0.9	0.6

6.1.7 Boiler cycling

As described in the literature research (section 2.3.3), in general terms, boiler efficiency can be optimised by lowering supply/return temperatures and reducing cycling. These two levers for efficiency improvement tackle latent heat recovery and start/stop losses respectively, with the reduction of the latter also benefitting hydrocarbon and CO emissions.

Using the same boiler power data from the EMS data, post processed into CH and DHW boiler operation using concurrent flag/diverter channel, the duration of every heating boiler operation could be derived using a simple MATLAB script, simply defined by non-zero modulation levels, bookended by 2 subsequent 0% modulation measurements. Data was recorded in fixed timestep, therefore counting and then scaling by the timestep resulted in a derived dataset of CH ON cycle durations (ON to OFF) taken from the complete measurement period, including transitional and summer months.

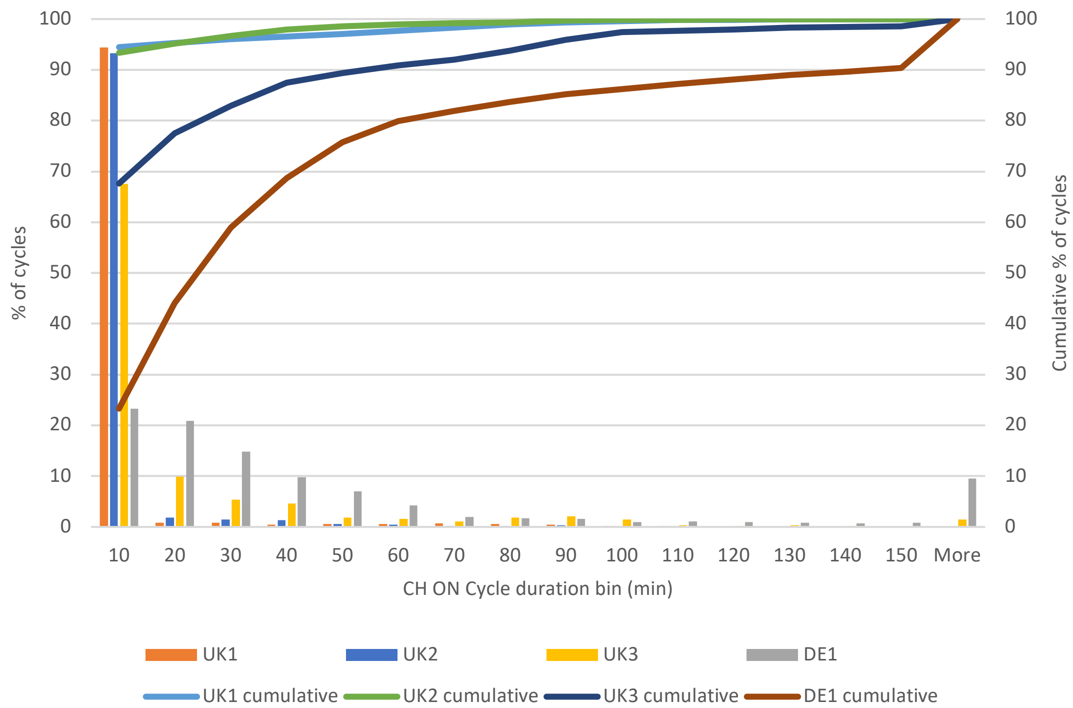


Figure 100: Histogram of heating cycle ON time duration for houses in Dataset A, 10min bin size

The combination of boiler output oversizing compared to the building heat load, specifically the minimum modulation point, and the probable restricting effect of the radiators' capacity, even before considering the compounding effect of TRV operation, will lead to the level of cycling seen in Figure 100. Analysis across the 4 houses in Dataset A shows markedly different cycling behaviour, with a tendency for longer cycles that follows the expectation based on plant size ratio from theory and simulation in this thesis. Figure 100 shows, the distribution of heating cycle length for the 4 houses under observation. Notable is that UK1 and UK2, with similarly sized combi appliances in buildings with similar heat loads (PSR at min CH 0.9 and 0.7) had almost all CH cycles of less than 10minutes (94 and 93%). Although UK3 has a PSR of 0.8, sitting neatly in between that of UK1 and UK2, the length of CH cycles is longer with 32% lasting longer than 10minutes. One difference between UK3 and the other UK houses, which could be of influence here, is improved control algorithms from the modulating weather compensated control, which can more effectively modulate the boiler power level to the current requirement and approach setpoints in a proportional manner. Whether the emitter sizes are less restrictive in this case cannot be derived from the data directly, but lower flow and return temperatures could be indicators of different emitter use and will be looked at later in this section. Larger emitter capacity can extend CH cycle times by enabling more heat to be transferred to the building, avoiding the return of hot CH water to the boiler requiring reduction of the boiler modulation level below its minimum achievable setting. In the German building, DE1, the difference is more pronounced; 23% of cycles measured less than 10 minutes, with many more falling between 10 and 60 minutes, and 10% lasting longer than 150minutes. Factors that have enabled most cycles to be in the range 10-60 minutes could be:

- More favourable PSR, of 0.6 at min CH load (made possible by 1:10 modulation level despite the lowest building heat load).
- Weather compensated control.
- More suitable emitters.

But it is worth noting that DE1 also lacks underfloor heating. CH cycles of longer than 150 minutes, which are absent for UK1/2 and account for just 1.4% in UK3 should be seen in the context of the different heating schedule in DE1 which closely resembles the daytime/night-time schedule type from the German national standard (DIN, 2011b) where heating is set to 21°C at either 0500 or 0600 and is setback to 16°C at 2200 or 2300. In colder winter months, the fact that the heating is never really 'OFF' certainly allows longer cycles to be possible, although the conditions of low PSR, modulating/weather compensating controls will also help. The UK buildings, by contrast, have bi-modal heating patterns with no setback temperature, or in the case of UK1 even tri-modal (morning, midday and evening heating). The UK style programmed heating schedule gives a hard time duration limit above which a boiler will not operate. Although the morning and evening heating schedules are longer than 150 minutes (and therefore a boiler cycle of this length is theoretically possible), it did not occur during the period of observation for UK1/2 and is only rarely seen in UK3.

Research (Orr et al., 2009) has shown that parasitic style losses from pre and post purge activities, necessary in condensing boilers from all manufacturers, play a more important role when the ON period of cycling behaviour drops and was noted as especially significant below 10 minutes. Although in Figure 100, differences in the behaviour of the heating systems can be seen for durations of cycle above 10 minutes, an additional closer look at cycles below 10 minutes is presented in Figure 101. Analysing on a 1-

minute resolution as in the figure shows that for UK1 and 2 the cycle times are lower than was apparent from the previous chart, both with over 50% of cycles lasting no more than 5 minutes. In contrast to the hierarchy of cycle durations shown at the 10 minutes duration, UK3 showed the largest proportion of cycles of duration 1 minute, but at 2 minutes it shows again the tendency to longer cycles.

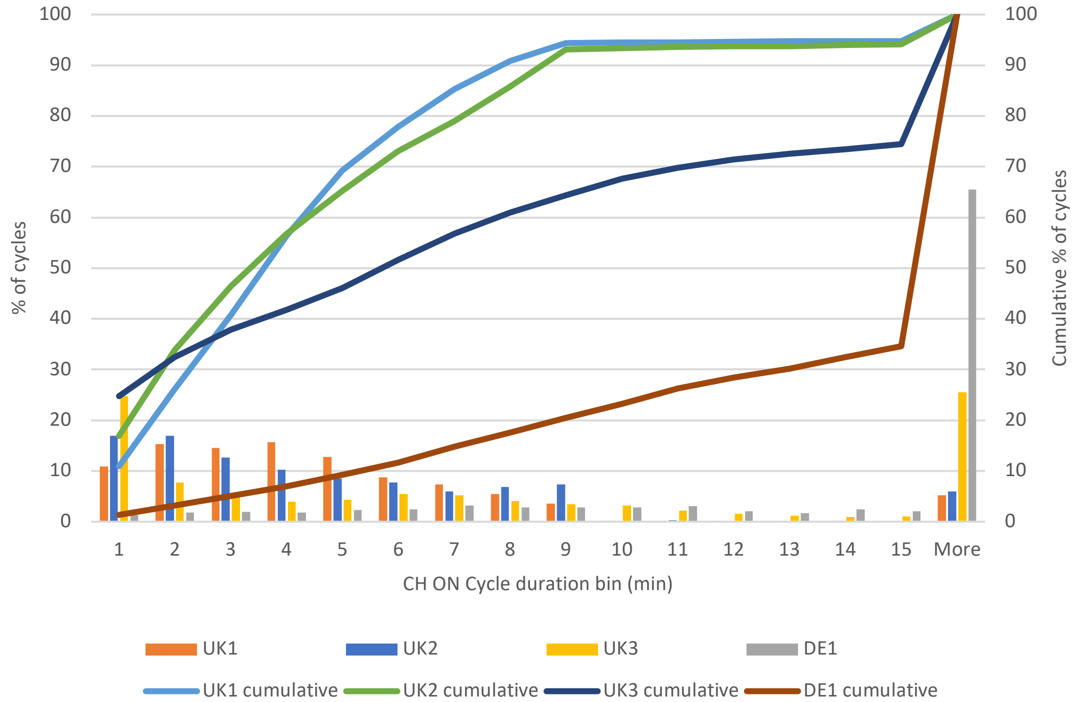


Figure 101: Histogram of heating cycle ON time duration for houses in Dataset A, 1min bin size, max 15minute

6.1.8 Supply Temperature distribution

Looking at some selected winter days has raised differences and similarities between the four houses under observation. Interesting differences emerged, with UK1 demonstrating more cycling behaviour in CH mode even when not interrupted by DHW demand, and DE1 exhibiting the other end of the spectrum with longer continuous boiler firing. In terms of heating system, the main differences between these two extremes (with UK2 and 3 bridging the divide) are the boiler type, with the implication on boiler power range, and the control method.

Whether the generally higher power output of combis has led to, in these cases, a fundamental thermodynamic inability to provide CH power at an appropriate level for maintained equilibrium is a question that will be analysed in more depth in the next sections when, with the aid of derived building heat loss, the relative power capabilities can be assessed. However, by looking at the cumulative effects of the other phenomena seen in the data so far, the performance of the boiler/heating system combinations can be further unpicked.

As discussed in the background of this thesis (section 2.3.3), two important parameters influencing boiler efficiency are return temperature and cycle length due to the increased propensity for scavenging of latent heat through condensing and reduced significance of start/stop losses/emissions respectively. Although not all heating systems in the sample were fitted with return temperature sensing equipment, by looking at the supply temperature, which was always logged in the same manner via the boiler, some light can be shed on the magnitude of the return temperature, and therefore the probable instantaneous likelihood of condensing. The return temperature of the CH water coming back from the heating circuit to the boiler cannot be at a higher temperature than that leaving the boiler as supply temperature, therefore when the boiler reports delivery of CH supply water at 50°C then the boiler is almost certainly condensing. A supply temperature of 80°C, however, does not preclude that the simultaneous return temperature is not in the condensing range, but certainly the probability is less.

In Figure 102, the supply temperature histograms of the four boilers have been plotted, after filtering according to the CH flag and non-zero boiler power level, therefore capturing only the periods when the boiler is actively heating the property. Although the CH pump does continue to run during CH mode after the burner has stopped firing, the CH supply temperature encountered in this passive heat distribution mode is not relevant since there is no opportunity to condense combustion products.

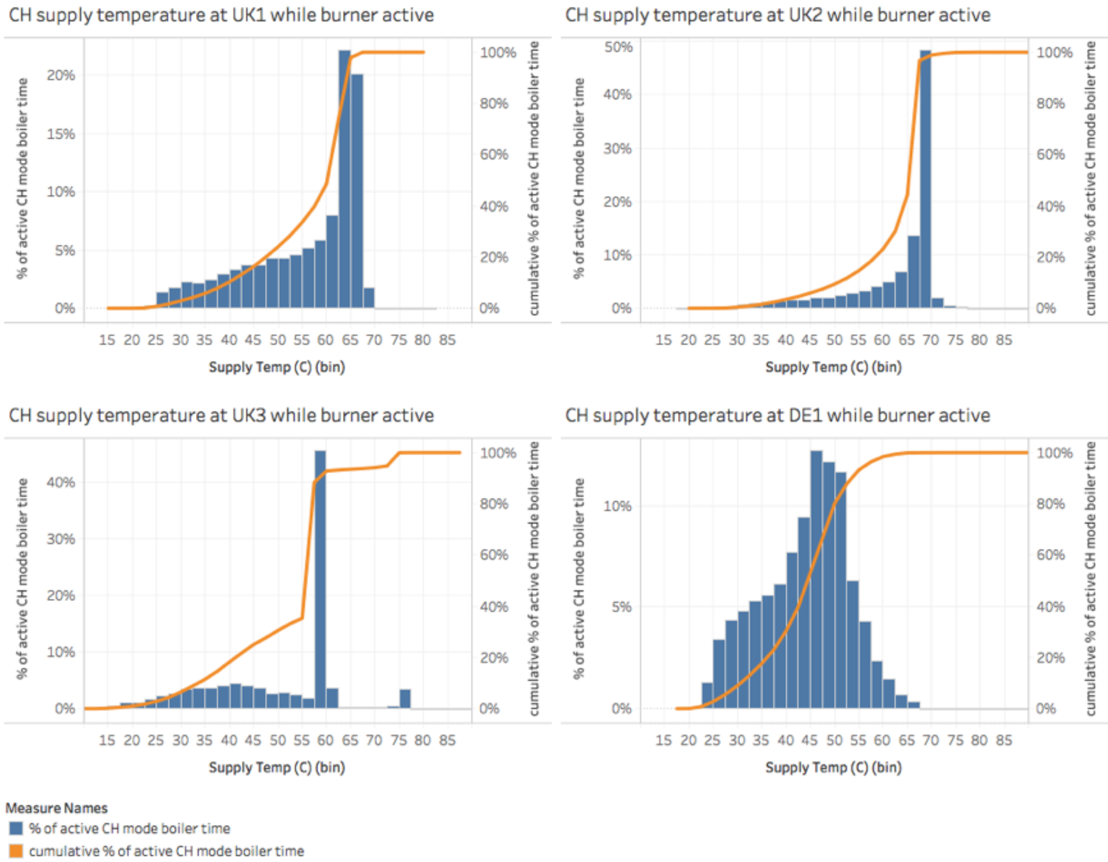


Figure 102: Histograms of supply temperature, while burner active, across UK1-3 and DE1

All the UK properties show a narrow peak of boiler activity accounting for at least 20-40% of the active CH boiler time. These peaks occur at 62.5-67.5, 67.5-70 and 57.5-60°C for UK1-3 respectively, with UK3 exhibiting an additional peak at 75°C. All of which indicate an operating mode predominantly above the condensing temperature zone of the boiler. The supply temperature is likely centred on a fixed parameter setting, probably directly taken from the user interface. DE1, however, has a more normally distributed supply temperature, with 50% of the operating time below 42.5°C. Given that, from the daily analysis, DE1 showed a relatively constant 10°C temperature difference between supply and return this points to a predominately condensing boiler operation in DE1.

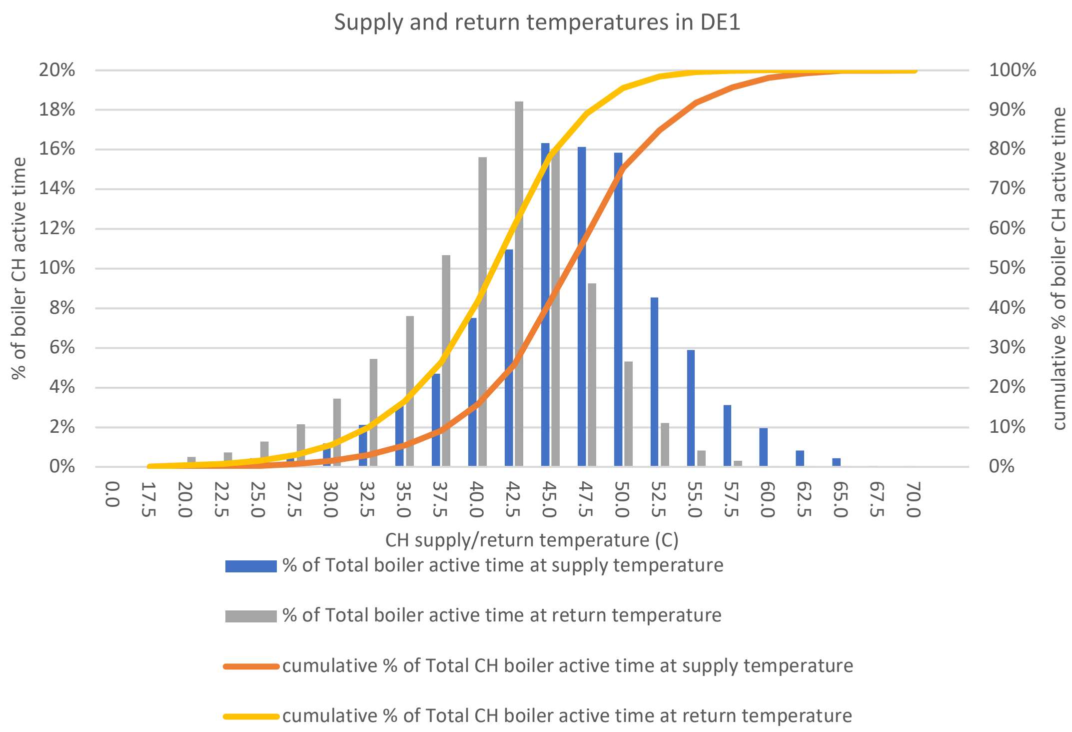


Figure 103: Building DE1 supply and return temperature histograms

The condensing behaviour of DE1 is elaborated upon by the data plotted in Figure 103, where both the supply and return temperatures are plotted for DE1. The data shows the shift of return temperature distribution compared to supply temperature, and a median value of 41°C return temperature confirming a high level of condensing operational time for the boiler. Whether the more favourable boiler operating conditions of DE1 are related to better sizing of the boiler, better control algorithms, longer scheduled operating times, hydraulic variables or a mixture thereof is not yet clear, but the indicators so far point towards the boiler size/modulation range and control methods.

6.1.9 Boiler power, supply temperature relationship

Looking at the distribution of supply temperature from another perspective can also deepen the understanding derived from the previous histogram figures. Scatterplots of supply temperature against boiler power for each property are plotted in Figure 104, where each data point represents one raw measurement point, with no averaging. The data point visualisation has been colour-coded to distinguish CH (blue) from DHW (red) operating modes, and opacity has been given to enable identification of regions of higher data point density.

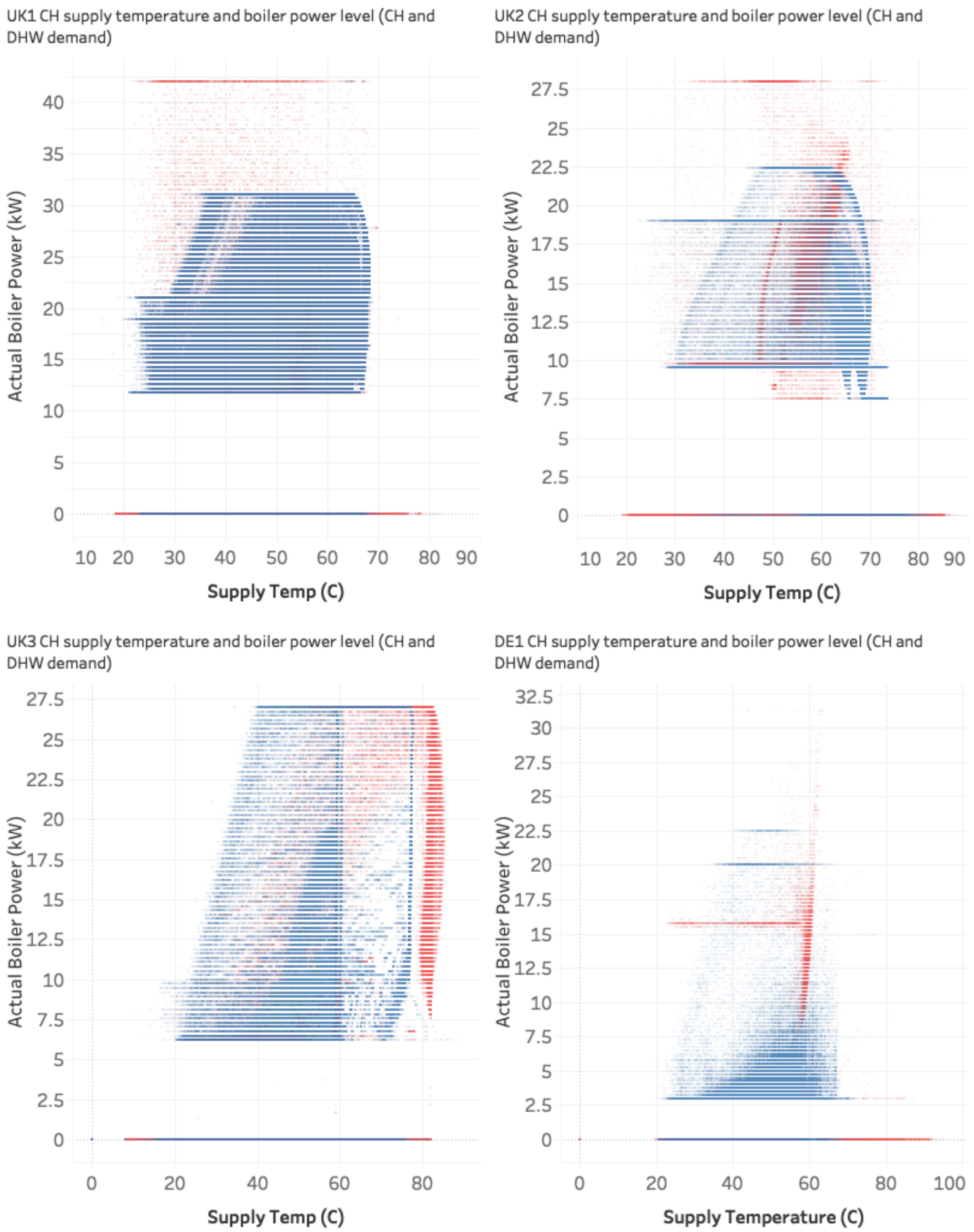


Figure 104: Scatter plots of supply temperature and boiler power level for all houses, CH in blue, DHW in red

The presentation of supply temperature data in the power domain shows how the boiler controls two of the major parameters at its disposal and where in the allowable operating envelope, the boiler mainly operates.

The power output range difference between CH and DHW for the combi boilers in UK1 and UK2 is visible where DHW power is used at higher levels than CH. For CH operation in UK1 and UK2 there is a distinct operating window within which the boiler mostly operates. The upper and lower CH power boundaries are clear for UK1, and correspond with the boiler specification; UK2, however, shows a fixed ceiling but two distinct minimum levels, one at 9.5kW and one at 7.5kW, with the latter only coming into effect at supply temperatures above 65°C, although this is the designated minimum CH power output of the boiler. The upper limit of the supply temperature in both UK1 and UK2 cases presents itself not as a constant although this is nominally a user-settable parameter. The upper bound is a convex curve dependent on power level, reducing the maximum deliverable supply temperature at both minimum and maximum power levels. In UK3 two frequently utilised supply temperatures can be seen in the CH data, but for DHW the boiler clearly aims to keep the supply temperature delivered to the tank constant while varying the power level, a mode of operation not possible in the combis of UK1 and UK2. The combination of low supply temperature and high-power output is not able to be utilised in any of the boilers in CH mode, an understandable limitation since the maximum flow rate through the heating circuit is limited by the hydraulic resistance and pump head. As with the supply temperature histograms before, DE1 stands out with a fundamentally different distribution of data points, clustered around the lower end of the modulation range and rarely venturing up into the higher echelons of the available power range except in DHW mode.

6.1.10 Boiler power modulation level

A recurring theme in the analysis of winter days in the 4 buildings of the dataset, was that despite the cold outside temperatures experienced by the building, the heating system would, inevitably have to curtail operation and enter a cycling operating mode to maintain the temperature. Although some of this effect could be due to the control system, the question is raised whether the average delivered power during that period is within the operating range of the boiler, i.e. would the system be able to react and track the heat load with an ideal control system. To look into this aspect further, the disaggregation of the boiler power channels was carried out to isolate only the CH operating time and level, and then this was averaged over each calendar week, but only for the hours of the day when the heating control was programmed to deliver heat, so night-time/daytime off periods (as in the UK buildings), and also setback temperatures were excluded. Average boiler power in 'CH heating ON' mode was then plotted along with outside temperature (also filtered as per the CH power) for reference and, crucially, the minimum modulation level for the installed boiler in that dwelling.

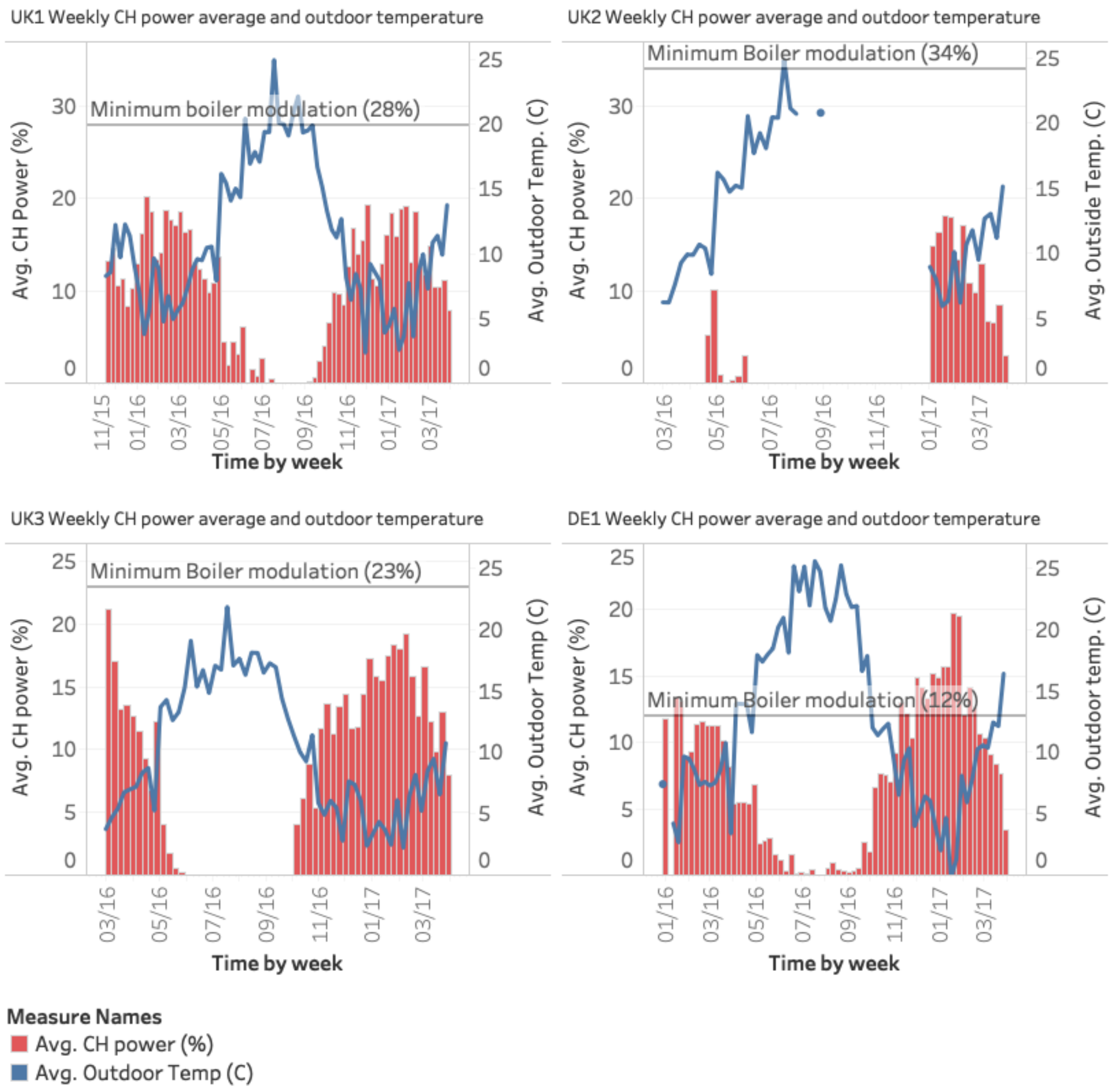


Figure 105: Weekly CH power level (in red bars) and outside temperature (blue line) for all buildings

The results in Figure 105 show clearly that for all houses, except DE1, the average CH heating power delivered during the heating demand periods was below the minimum possible modulation level of the boiler, implying that regardless of the control mechanism the boiler would always be forced to cycle, within the range of outdoor temperatures experienced during field measurements. In DE1 the conditions were such that a lower minimum modulation level and lower outdoor temperatures combined to mean that from end of November 2016 until mid-February 2017 the heat load was within the capabilities of the boiler. In DE1 the outdoor temperature which corresponds to heat demand within the boiler range corresponds roughly to under 5°C although still at a maximum average weekly power of less than 20%, this allows the boiler to operate within its modulation range for some weeks, but still not all. If the other houses also had a boiler capable of the low modulation level of DE1 then they also would have had the opportunity to partly avoid cycling.

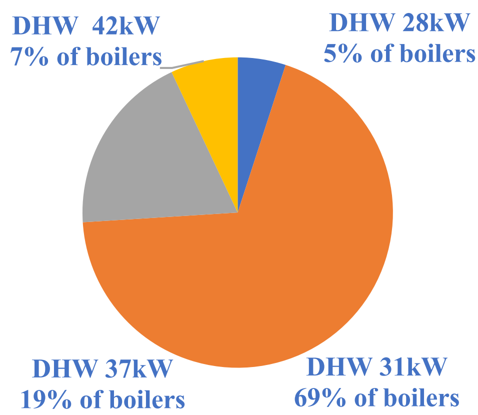
From the analysis of the detailed and high frequency data of the four houses under observation in Dataset A it was determined that boiler over-sizing is playing a role in the dynamic behaviour of heating systems, specifically in a negative way with regards to efficiency and emissions through increased propensity for cycling and short, high temperature operating periods when boilers are oversized. Secondary factors such as heating control type and heating schedule are also contributing to unfavourable conditions when the controls are ON/OFF and heating periods short. Whether the combination of the lower thermal output boiler in DE1 with a heating schedule of the UK buildings would result in an increase in efficiency, while maintaining the comfort requirement of fast warming within a short heating schedule, is not exactly clear from the data so far. Although the benefit of the wider modulation range is clear in bridging this efficiency/comfort gap and showed no obvious downsides.

After seeing the effects of PSR and controls in simulations, and now in a small number of real houses, what remains is a broader look at the general boiler population to discover if the effects seen so far are also widespread in the housing stock of the UK.

6.2 Empirical Dataset B: Boiler diagnostic data

Modern boilers manufactured by Bosch Thermotechnology have the facility to transmit the internal diagnostic data via the internet to a central server. The data is available via the proprietary Energy Management System (EMS) bus. A download of boiler data logged from February 2014 to August 2015 was made available as common '.csv' files, one per boiler from a sample of 217. Each boiler records a total of 109 variables.

Boiler DHW max. output distribution in Dataset B



Boiler CH output distribution in Dataset B

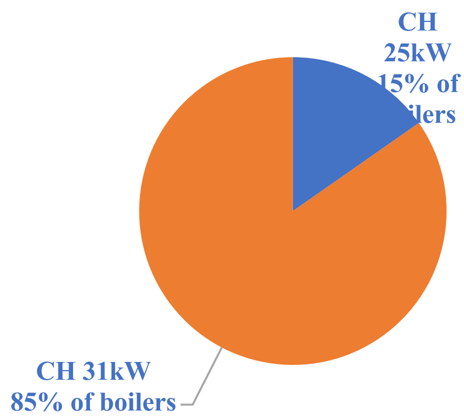


Figure 106: Distribution of Nominal maximum Burner Power of the appliances

Although the details of the buildings in which these boilers are installed is not known, and therefore a direct assessment of the suitability of the boiler thermal output to building thermal load cannot be made, a qualitative comparison with the estimated space heating load of the UK housing stock shows that even the smallest recorded boilers (28kW DHW 25kW CH, Figure 106) are larger than would be normally necessary when considering a simple steady state heat requirement for the buildings. In Figure 107 the distribution of design building heat loss (Butcher, 2005)(-2°C outdoor, 21°C indoor, steady state) derived from the building stock data in the Cambridge Housing Model (Hughes et al., 2011), included in the CHM model is the fabric heat loss and ventilation loss as derived according to the UK Standard Assessment Procedure (BRE, 2014). Estimating the steady state design day heat loss in this manner shows that almost all buildings would require a boiler of less than 36kW output and 95% below 20kW, with a median value of approx. 6kW. CHM is a physical model which assumes standard values for thermal performance inputs (such as U value (Li et al., 2014)) and omits price elasticity and assumes a constant internal temperature requirement. Estimates based on real annual and quarterly domestic energy consumption estimate the space heating at 2.4kW with an external temperature of 5°C, noting that the energy demand plateaued at lower outdoor temperatures (Summerfield et al., 2010). Given this context, the probability that any given boiler from the dataset is oversized with respect to space heating requirement, is therefore large and should be considered in the following analysis. The primary reason for the disparity between the boiler output and building heat loss is related to the nature of combination boilers being sized according to instantaneous hot water demand. DHW peak power demand outsizes the space heating demand, therefore leading installers to size boilers on hot water only with little regard for boiler size relative to heating demand, known as the plant size ratio (PSR) (section 2.3.3.1) (Gleeson, 2015).

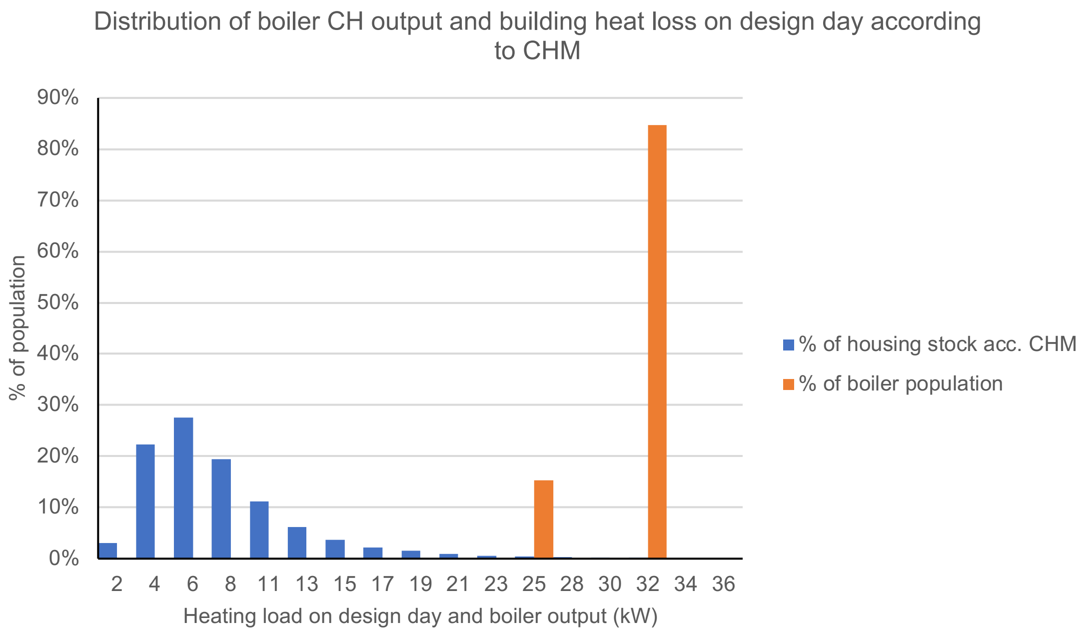


Figure 107: Distribution of building heat loss on design day acc. CHM (Hughes et al., 2011)

The steady state heat loss requirement of a building is only part of the picture and would be sufficient for heating system design in buildings where the operative internal temperature was required to be constant. However, variable heat schedules mean that the internal temperature needs to change in an intermittent manner and additional thermal power is needed to raise the internal temperature quickly in order to deliver the comfort the occupant expects; the response time will depend both on the building structure and the heating system (see the simulations in sections 5.2 and 5.4). Parameters such as thermal mass, heater thermal output, emitter size and temperature will all combine to determine the responsiveness of the internal temperature. Compensating for the intermittent heating schedule and considering the thermal response of the building from slow (masonry walls, internal partitions) to fast (lightweight external cladding, suspended floors and ceilings) first approximations of the increase in heating plant size can be seen in Table 1. The number of heating hours of a residential house is standardised as 9 hrs (2hrs mornings, 7hrs evenings) on weekdays and 16 hrs (as one block) at weekends in SAP, and also measured as between 6-14 hrs in field research (Huebner et al., 2013a); therefore the estimated requirement for plant oversizing (compared to first order steady state, heat loss only estimate) would be a maximum of 2 (section 2.3.2). This would push the median expected plant size up from 6 to 12 kW but only in the case of light construction fast reacting buildings: slower, more thermally massive buildings would not require such over-dimensioning since the internal temperature will drop slower in between heating periods.

Plotting the annual space heating energy (the calculation and distribution of which is elaborated upon in the next section) against boiler CH output against the annual space heating energy in Figure 108, shows again that there is a weak or no correlation between the size of the boiler and the heating demand, implying no plant sizing according to the building thermal load has been done before selecting and installing a boiler. This result mirrors the findings of the extensive report into boiler performance prepared for the Energy Savings Trust (Orr et al., 2009)

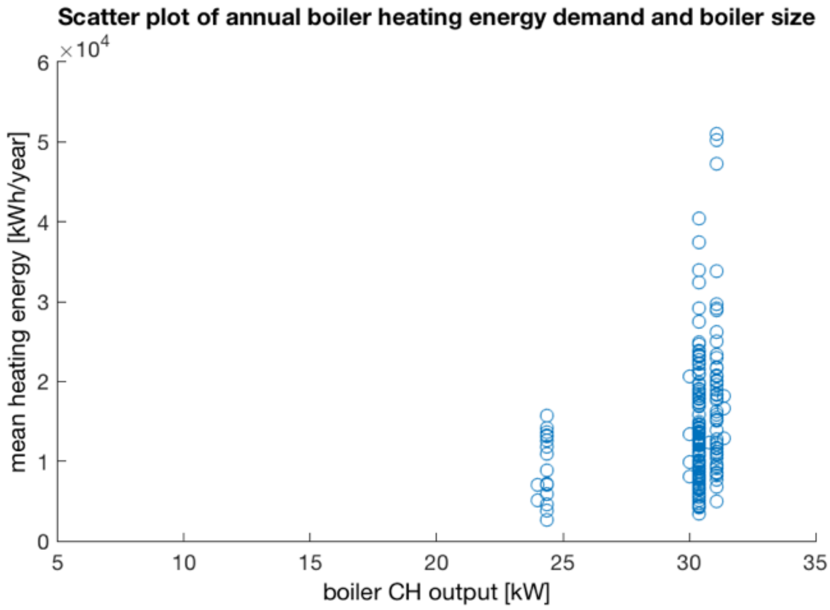


Figure 108: Scatterplot of boiler CH output and annual space heating demand

6.2.1 Space Heating

Using the logged boiler thermal power level data, CH/DHW mode flags and the recorded thermal output of the boilers, it is possible to integrate the delivered annual thermal energy (Feb 2014 to Feb 2015) to the heating circuit separately to the DHW. Further comparison with the estimated annual space heating from CHM is therefore possible and presented in Figure 109. First assessment shows that despite the significantly larger boiler size than UK building stock would require, (linked to increased energy consumption in the simulations in this thesis (Bennett et al., 2016) and lowered efficiency (Heselton, 1998)), heating energy demand is of the same order of magnitude with a median of 12,400kWh/year compared with 16,000 kWh/year from the CHM for the building heat demand. CHM contains buildings with heating demand of more than 50,000kWh and a number of buildings with higher heating demand, whereas the measured boiler sample does not, possibly due to the lack of combi boilers in larger buildings with multiple bathrooms despite sufficient boiler heating capacity. The measurements and the CHM data are broadly similar and will be taken as being approximately representative of UK residential heating demand providing insight into the performance of the wider UK stock; further research is required to determine the distribution of heat demand across the UK.

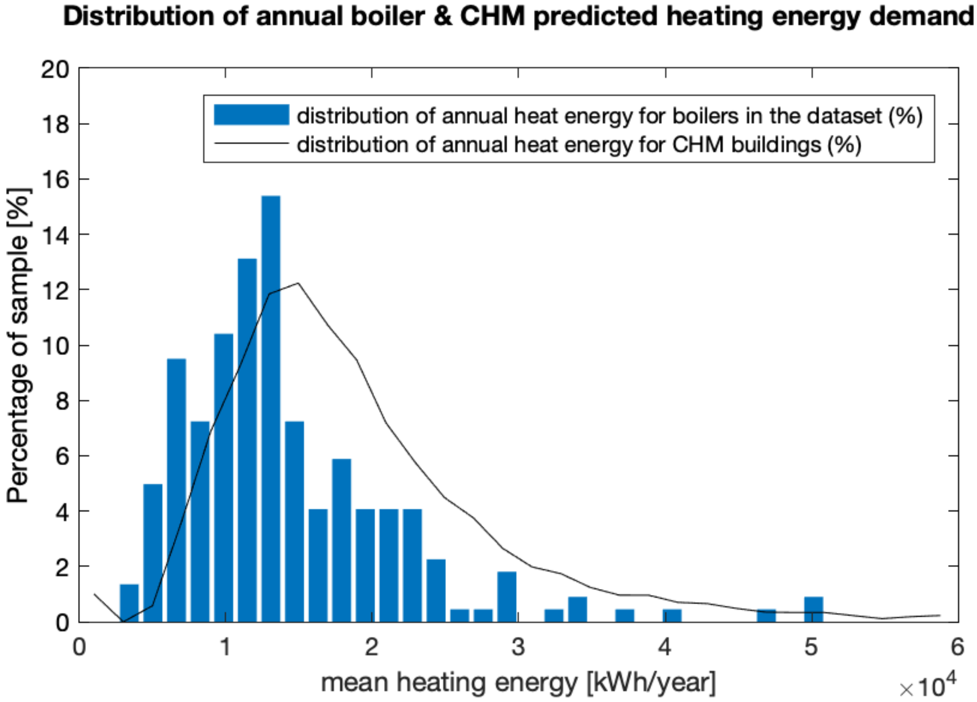


Figure 109: Annual building heating energy demand (Hughes et al., 2011)

The data was broken down further to analyse the space heating demand on a monthly basis. Typically, and in SAP, the UK heating season is October to end of May. From the data shown in Figure 110 however, there are a number of cases where the boilers are still providing space heating in the summer months (June to September inclusive).

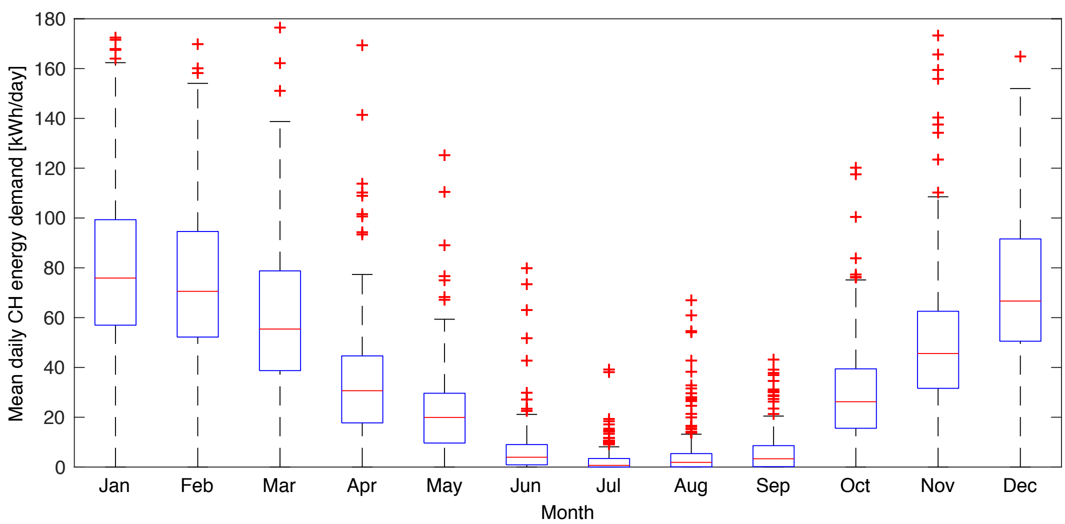


Figure 110: Daily CH heat demand boxplot (box: 25th to 75th quartile, red crosses: outliers)

Although the energy demand level may seem small in the summer months, two factors should be considered in the context of summer heating. Firstly, SAP and other energy demand type methods consider that the space heating would be zero during these months, so any households consistently still using heating in summer are poorly characterised by such models. Secondly, as was seen in the simulations in previous sections and the field assessment of the EST (Orr et al., 2009), the efficiency of boilers is significantly decreased during periods of cycling and when daily demand levels are, on average, low. It is still possible that with a small number of high-power heat demands that cycling could be limited, for example with morning heating or hot water tappings. However, it is likely that the summer months are precisely the type of thermal condition that could lead to sub-optimal operation of boilers. Effectively the oversizing and intermittency that has been shown to decrease efficiency is exacerbated in the summer months as the building heat load drops to a level where modern boilers certainly cannot modulate low enough to continuously follow the demand. It could be that operation of boilers in summer and the shoulder/transition seasons is having an environmental effect which outweighs the heat demand that is being delivered. Lower efficiency of the boiler and the increased cycling could be leading to larger than normal gas demand and start-up emissions.

6.2.2 Boiler cycling and start-stop behaviour

In the following analysis, a distinction is made between a heating demand (Domestic Hot Water, DHW or Central Heating, CH) and a boiler start. In the case of a combination boiler a heat demand will occur either when a hot water outlet (tap, shower etc.) is opened, and the flowrate is above a predetermined threshold or, when the room thermostat makes a call for heat to raise the internal temperature to the required setpoint at that time. However, heat demand needs to be differentiated from boiler start. In the case of DHW the relationship is direct since the demands are equivalent to the boiler starts; the boiler directly recognises the flow of water to the hot water outlet via a turbine and initiates the burner start sequence. Combination boilers will always give priority to DHW demands on the basis that a short interruption in space heating will not be noticeable when compared to delayed hot water.

Starts due to space heating demand are triggered by the room controller which can vary in complexity of internal algorithm and the richness of the communication with the boiler (section 2.3.7). Thermostatic controllers (time and temperature dependent) and timer clocks (time dependant only), where the demand for heat is a binary, relay type, signal to the boiler are the most basic forms of control, these types of simple controller were the case for all the boilers under investigation in this research, not because of any filtering criteria, but because this would seem to represent the general state of installed heating controls in the UK. The two are indistinguishable in the dataset since both send only a binary signal to the same input of the boiler.

The universal presence of these simple controllers is important in the analysis due to the highlighted control conflict issues that can arise when room temperature control clashes with internal boiler temperature control algorithms, especially in cases of oversizing (section 2.3.3 and 2.3.7).

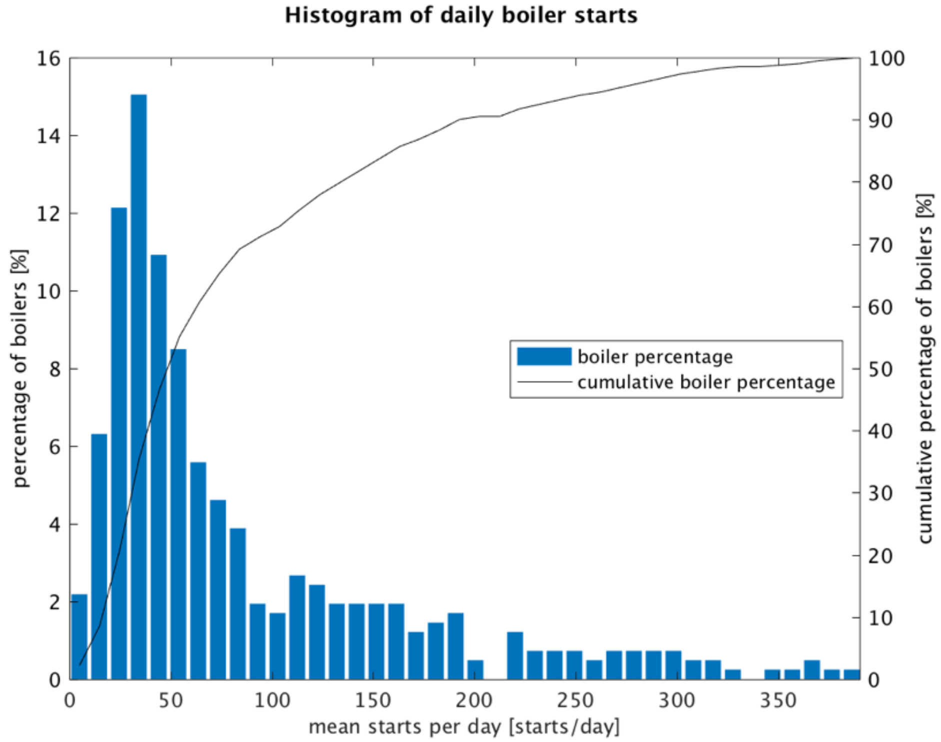


Figure 111: Distribution of total annual boiler starts

From Figure 111 above a wide range of daily boiler starts can be seen where 70% of boilers have less than an average of 100 starts per day. On average this would be 4 starts per hour. The median of 53 boiler starts per day, contrasts starkly with the mean of 93, reflecting the extended tail of boilers with high daily boiler starts.

In order to unpick this number of starts and to put it into context, analysing the CH/DHW digital flags from the EMS allows the differentiation of the starts according to the associated heat demand type. Removing the DHW starts (which will be discussed in detail in the following section) and focussing on the genuine CH starts leaves a distribution of average starts per day during the heating season (October to May). If a theoretical heating system (infinitely modulating with instantaneous heat delivery) is considered operating on a degree day, then according to the bi modal heating schedule specified in SAP (BRE, 2014, BRE, 2010) and observed in practice (Huebner et al., 2013a), one could ideally expect only 2 central heating starts per day, one in the early morning and one in the late afternoon. Bearing in mind that combination boilers will inevitably experience priority DHW demands during space heating operation then this idealistic situation is clearly unrealistic. Transitioning from CH to DHW or back, always results in temporary cessation of the burner flame and circulation pump in order to allow the time for the diverter valve to move (which is best done in a no flow situation) and to ensure that the output temperature is controlled adequately, which is not always possible if the transition was instant, and is especially important for DHW temperature control and avoidance of scalding. In addition, transitional periods at the beginning and end of the heating season will result in heating demand that is not constant during the daily heating schedule. Solar gains increase and heat loss to the environment decreases, further increasing the likelihood of premature satisfaction of the heating demand, although outdoor temperature compensation and variable schedule controls could be used to offset this effect. However, around half of the boilers under investigation had average daily number of CH starts above 50, as shown in Figure 112. Even considering DHW demand interruptions and transitional heating days where partial heating is required and the boiler will cycle as a result, it is clear that some other phenomena are involved which lead to the high number of starts. The exact cause or whether this high number of CH starts is leading to either a drop in efficiency or an impact on occupant comfort cannot be directly determined from the dataset available. However, from the simulations in section 5.2 it was seen that for PSR 8.5 and 3 the cycles per day were between 60 and 30 respectively which does not correlate with the higher cycles seen here, but that level of cycling resulted in a simulated efficiency of 86 to 90%.

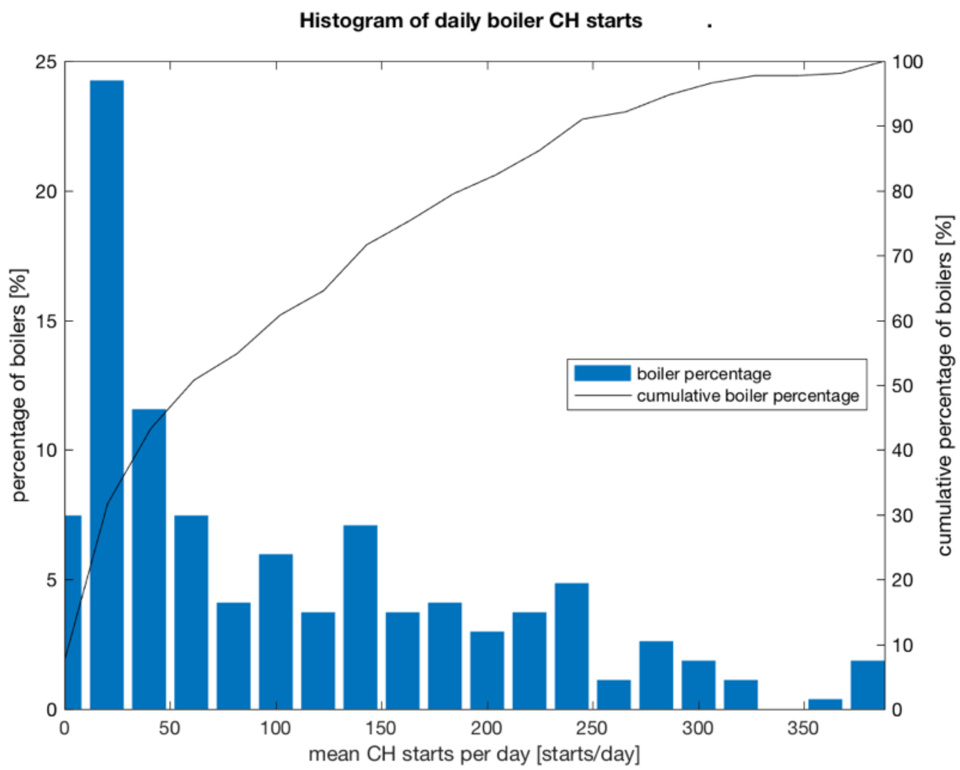


Figure 112: Histogram of average CH starts per day

Similarly, the duration of each CH boiler operation also deviates significantly from what would be expected in a heating system where the operating time is concurrent with the heating demand schedule and modulates to meet the minute by minute heat loss. SAP describes a standard UK heating schedule to be 0700 to 0900 and from 1600 to 2300 on weekdays and weekend heating times are from 0700 to 2300, which implies boiler running times of the order of hours, potentially 2-7hours. However, the boilers observed show average runtimes in CH mode in the range of 1-30 minutes, with 70% of boilers averaging under 10 minutes. This supports the findings in the case studies of Dataset A where all dwellings had the most starts shorter than 10 minutes with the UK buildings all having more than 65% less than the 10-minute threshold.

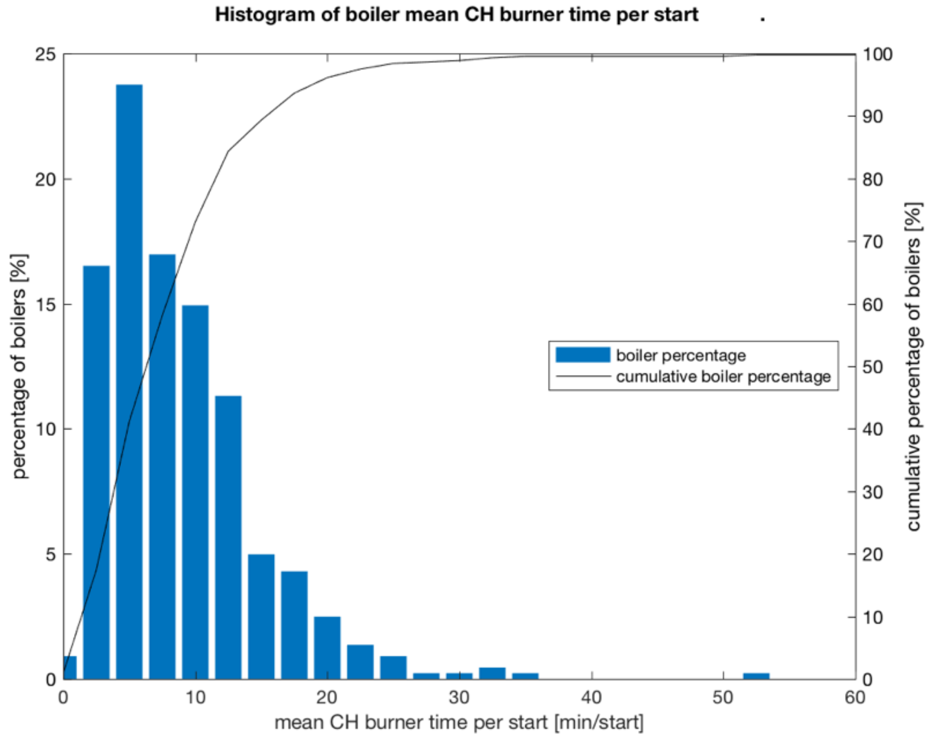


Figure 113: Histogram of average CH runtime per start

Considering the observed cycling behaviour in simulation and its connection with boiler oversizing and lower efficiency these trends in this larger dataset are both a cause for concern due to the implication of poor in situ performance and reassuring that a possible mechanism is observable.

6.2.3 Domestic Hot Water

In contrast to the space heating behaviour of the boiler in the building where analysis is limited due to missing meta data, these limitations are not so great in the case of hot water usage. In fact, because of the more detailed nature of the information logged by combi boilers, novel analysis avenues can be followed compared to the literature. However, the DHW data from the boiler does not cover additional sources of hot water demand in the dwelling such as electric showers, dishwashers and washing machines.

Due to the direct correlation of DHW demand and DHW start the histogram shown in Figure 114 can be directly compared with EN13203-2 (CEN, 2015a), the European norm used for heating appliance performance testing for hot water production which also excludes dishwashers and washing machines, allowing a better comparison here, although electric showers would still be an additional DHW demand not provided by the boiler.. EN13203-2 groups hot water consumption into S, M, L, XL and XXL and states that the profile S represents a single person household, M an average family (the mean European hot water consumption), whereas L stands for a family with three persons using both shower and baths.

Table 25: DHW standard profile summary from EN 13203-2(CEN, 2015a)

Load profile type	S	M	L	XL	XXL
Energy demand [kWh/d]	2.1	5.845	11.655	19.07	24.53
DHW consumption [l/d]	36	100	200	325	420

The DHW consumption shown in Table 26 is defined as the volume of water delivered at 60°C which represents the daily energy of the load profile type. Each profile (S-XXL) is made up of a time series of different tapping types. Further detail is given in the standard regarding the different tapping types summarised in Table 26. This is used together with a daily time schedule to allow performance testing of hot water heaters, including gas combination boilers. The inclusion of such dynamic test profiles recognises, in part, the impact of transient behaviour on the efficiency of heating systems, the significance of which is only partly acknowledged in the space heating domain.

Table 26: DHW tapping types from EN13203-2

Type of Tapping	Energy demand Q [kWh]	Flow rate [l / min]
Small tapping	0.105	3
Dish washing 1	0.315	4
Dish washing 2	0.420	4
Dish washing 3	0.735	4
Large tapping	0.525	5
Household cleaning	0.105	3
Showering 1	1.400	6
Showering 2	1.820	6
Floor cleaning	0.105	3
Bathing 1	3.605	10
Bathing 2	4.420	10

Showering and bathing	6.240	16

Simple comparison of the average boiler DHW starts recorded with the standard is shown in Figure 114. There are a small number of boilers making high numbers of DHW starts, but the median is 18 tappings and mean is 36 per day. From the L and XL size tapping profiles of EN13203-2 (DHW production efficiency testing standard), between 19 and 24 tappings per day are stipulated, which broadly agrees with the average values see from the data in Figure 114. But with a quarter of households in this sample making more than 40 tappings per day then consideration should be given as to how this impacts on the national hot water demand, and the representative distribution of light and heavy users of hot water.

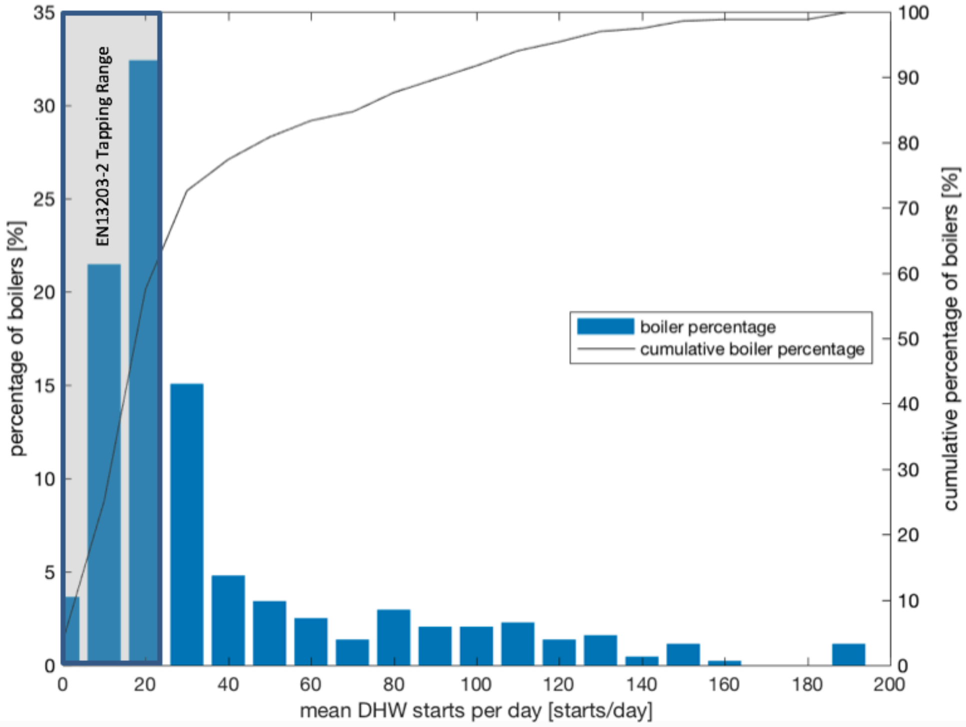


Figure 114: Histogram of mean DHW starts per day (with EN13203-2)

According to the metric of litres of hot water consumed per day then the range of standard volumes (36-425 litres/day) covers all but the most extreme boilers from the sample, as seen in Figure 115.

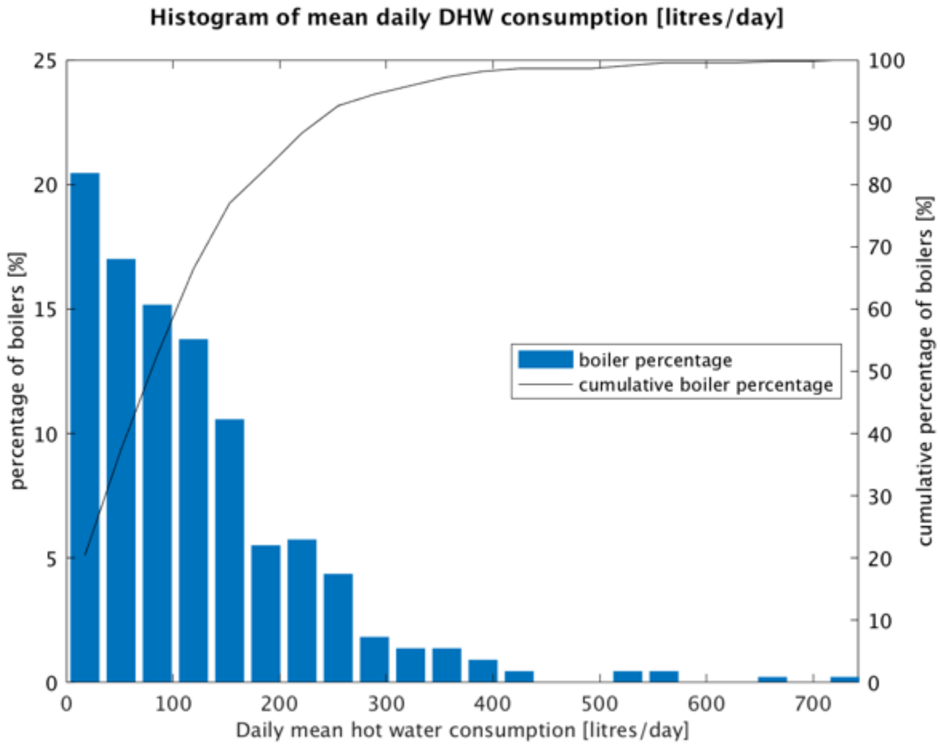


Figure 115: Histogram of daily mean hot water consumption

The following pie chart shows the percentages of boilers in the sample that fall into the various categories of the EN standard. Since the standards specify a single value of water volume then the boilers have been separated according to the inter category range. It is interesting to see that more than 60% of the boilers fall between S and L limits (36-200l/day). It would seem that the larger profiles, certainly in terms of water consumed by combi boiler households, are not representative of many households, but the 21% of boilers that consume an average of less than the smallest category (36 l/day) are significant.

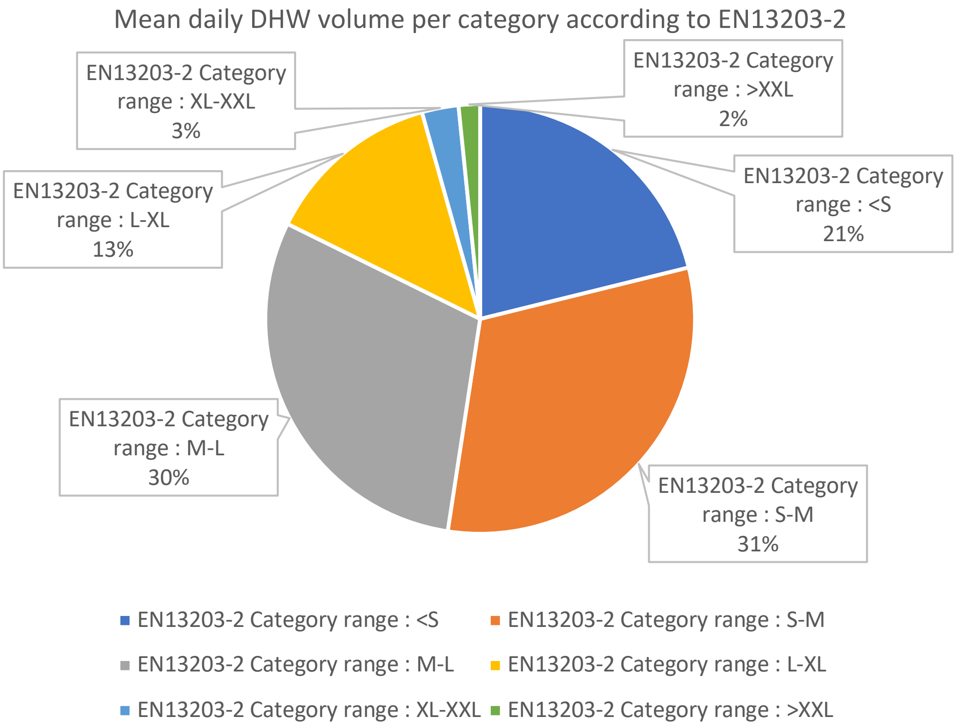


Figure 116: Categorisation of boilers' mean daily hot water consumption according to EN13203-2

The Energy Savings Trust also conducted an extensive study of UK hot water consumption (EST, 2008) which also pointed towards consumption levels larger than the smaller EN standard categories

Table 27: Summary of Boiler DHW tapping, number, volume and duration

Source	**Daily run-offs/ tappings**	**DHW mean consumption [litres/day]**	**Mean tapping duration [min:sec]**
EN 13203-2, cycle S	10	36	0:59
EN 13203-2, cycle M	23	100	1:10
EST study (EST, 2008)	28	142	-
Empirical Dataset B	36	120	1:03

The high number of tappings compared to the standard and the relatively comparable volume of water is reflected in the low average tapping duration for the boilers, almost all boilers averaged, over the measurement period, a tapping duration of less than 2minutes, shown in Figure 117.

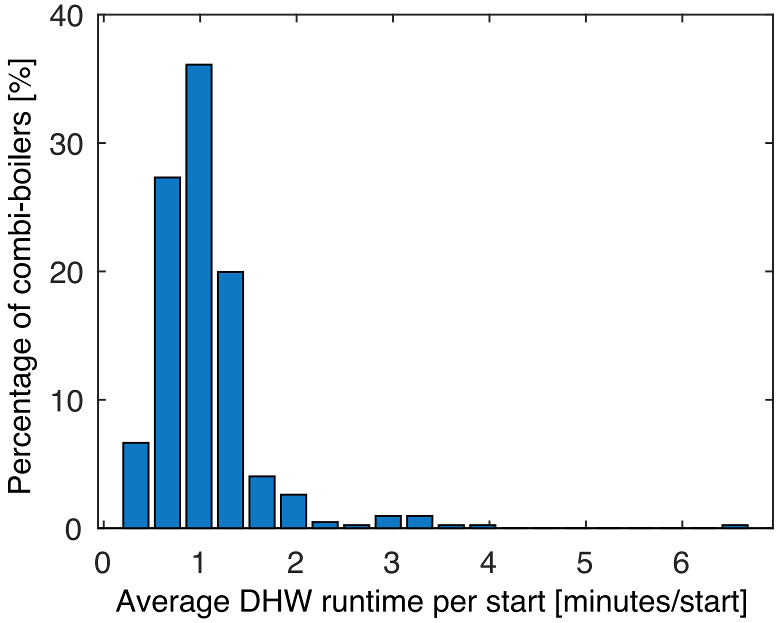


Figure 117: Mean tapping/DHW start duration

The prevalence of shorter tappings in the EN standard follows that of the data also brings the mean tapping time down, the longer bathing and showering demands are not occurring often enough to increase the average above 2 minutes. Shorter tappings dominate the DHW behaviour in households in terms of the number of starts.

The richness of the dataset available allows for a deeper analysis into the nature of the tapping profiles that occurred in the houses under observation. The combi boiler uses a flow turbine to sense and measure the cold-water inlet flow before it is heated and returned as hot water. Besides acting as a pseudo flow switch to trigger the boiler at >2l/min, the measurement continues throughout the tapping and, together with the DHW outlet temperature, allow the boiler to modulate the power level to achieve the desired hot water temperature. Both data channels were logged for the boilers under observation and the histograms of the average flow rate and temperature per tapping are shown below.

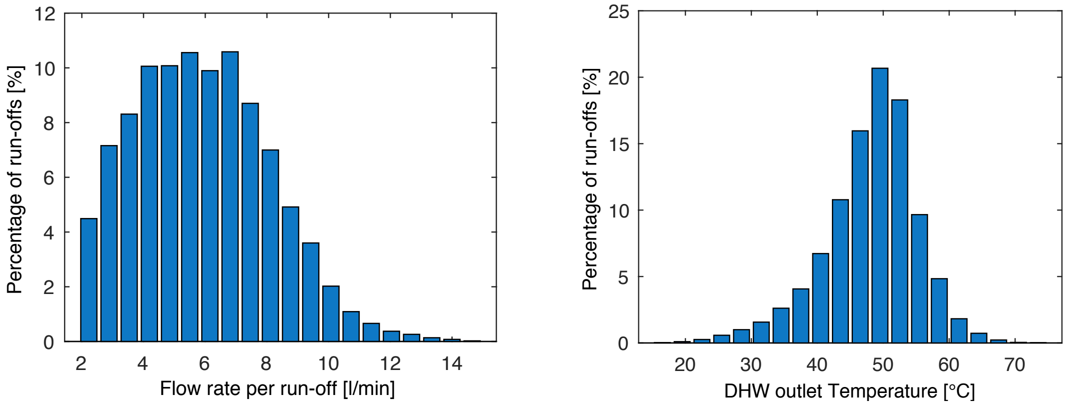


Figure 118: Average flow rates and outlet temperature per tapping run off

Despite a drive towards ever larger hot water production capability in the boiler industry, the flow rates of tappings and the temperatures indicate that the full capacity of the boiler is seldom used. The power capacity of the boilers in the sample is between 28 and 42kW, which is a range of 10 to 15 l/min for a 40°C temperature rise, equivalent to 50°C outlet temperature for a standard 10°C cold water mains inlet. Although the outlet temperatures are up to, and in some cases over, the maximum setting on the boiler, the flow rates are mainly below the boilers' capacities. It is possible other plumbing aspects shape the DHW demand such as pipework pressure drop, mixing taps and shower heads. Public information drives to use water saving outlets have had an effect on lowering the hot water demand below what was expected at the time of installation of the boiler or, as was suggested in the case of central space heating, boilers tend to be oversized by installers to avoid customer dissatisfaction.

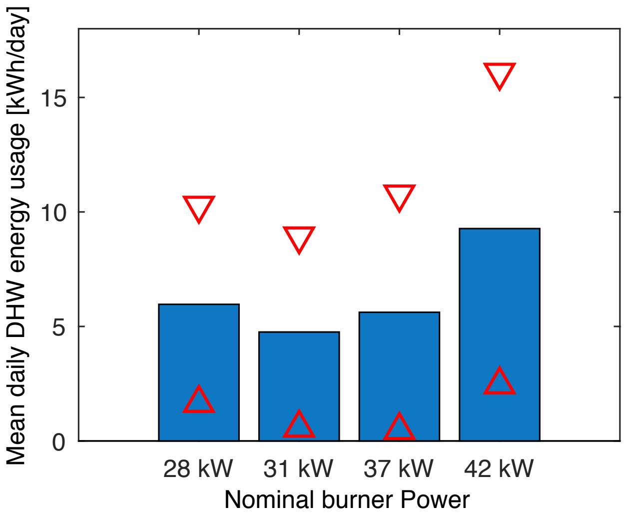


Figure 119: Boiler daily DHW demand per boiler output category, mean (blue) and Standard deviation (red triangles tip)

By segmenting the boiler daily hot water energy demand by boiler size, specifically the hot water output (since this differs from the CH output), then there is almost no correlation between boiler size and hot water demand. It can be seen that the mean and standard deviations for 28 and 37kW output boilers are similar, whereas the 31kW is actually lower than the smallest 28kW boiler. Only the larger 42kW boilers push the trend higher. It is generally assumed in the boiler industry that combi boilers are chosen on the basis of desired hot water capacity and are sized as such. This has the consequence of raising the minimum lower CH modulation level and, as we have seen in the simulations and monitored data, increases cycling behaviour. If, as lack of correlation between boiler size and hot water consumption would imply, there is no link between the size of the boiler and the actual consumed hot water, then it may be that consumers are sacrificing central heating performance for a hot water benefit that they rarely exploit.

6.2.3.1 Keep-hot function

Combi boilers, as well as delivering on-demand hot water, also feature a function to ensure that the on demand hot water is produced as quickly as possible. The details of how the function operates have already been seen and explained in the context of the case study of UK2 (section 6.1.2). Such functions are considered in the NCMs as an additional energy demand. The assumptions in SAP are 900 kWh per year for an un-timed keep-hot facility and 600 kWh per year for a Keep-Hot facility which is controlled by a time clock (BRE, 2010). With the dataset here, it is possible to compare these values to real data.

The keep-hot algorithm was seen operating in the analysis of UK2 day profile data (section 6.1.2) where the regular short firing of the boiler was evident during night time operation. The algorithm that controls the keep-hot function, if turned on via the boiler or system control, will monitor the internal CH water temperature and if it falls below a certain threshold, fire the boiler, to heat and internally circulate the CH water until the setpoint is reached. If a DHW tapping occurs before this energy is dissipated to the surroundings then the keep-hot function has fulfilled its purpose and the energy been used for the intended purpose. If the CH water temperature drops in the boiler while no DHW tapping is made and the keep-hot function is triggered again, then the energy has been wasted for DHW production but to answer if the energy is really wasted it needs to be considered where the heat is being transferred to and when. If the boiler is located within the heated envelope of the building then is it conceivable that the heat may be useful as space heating. Previous studies have found around 70% of boilers in the UK are installed in the heated space (Orr et al., 2009), leaving 30% in parts of the building where dissipated heat will not be used usefully. Of the 70% of boilers in the living space, seasonal and daily variation in the heating schedule will mean that lost heat will not always be useful to the occupier. In summer during the night time and daytime off periods the heat, although technically useful, may not be desired by the occupant.

Assuming that all thermal energy not utilized in the next tapping or central heating demand is wasted to the environment, i.e. the boiler is outside the heated envelope or the occupant does not need or want the extra thermal energy, then the associated losses may be estimated from the data, to count the energy not used by the keep-hot function to actually heat tapped water (Ramin, 2017). A visualisation of the algorithm function is in Figure 120. Since a real hot water demand is defined as a boiler firing triggered by a flow signal from the boiler flow turbine sensor then it is simple to detect a keep-hot firing, since the DHW flag will be active, but no flow or DHW temperature rise will be detected concurrently.

The unused energy for preheat describes the thermal energy used to heat up the boiler which is not used in a subsequent DHW or CH demand. The unused energy is dissipated to the environment due to heat losses. If there is a heat request from the user before the boiler cooled down to the lower temperature limit, the energy from the preheat start is partly used because then less energy is needed to heat up the boiler. The script loops through all load profiles and calculates the unused energy for every device (Ramin, 2017).

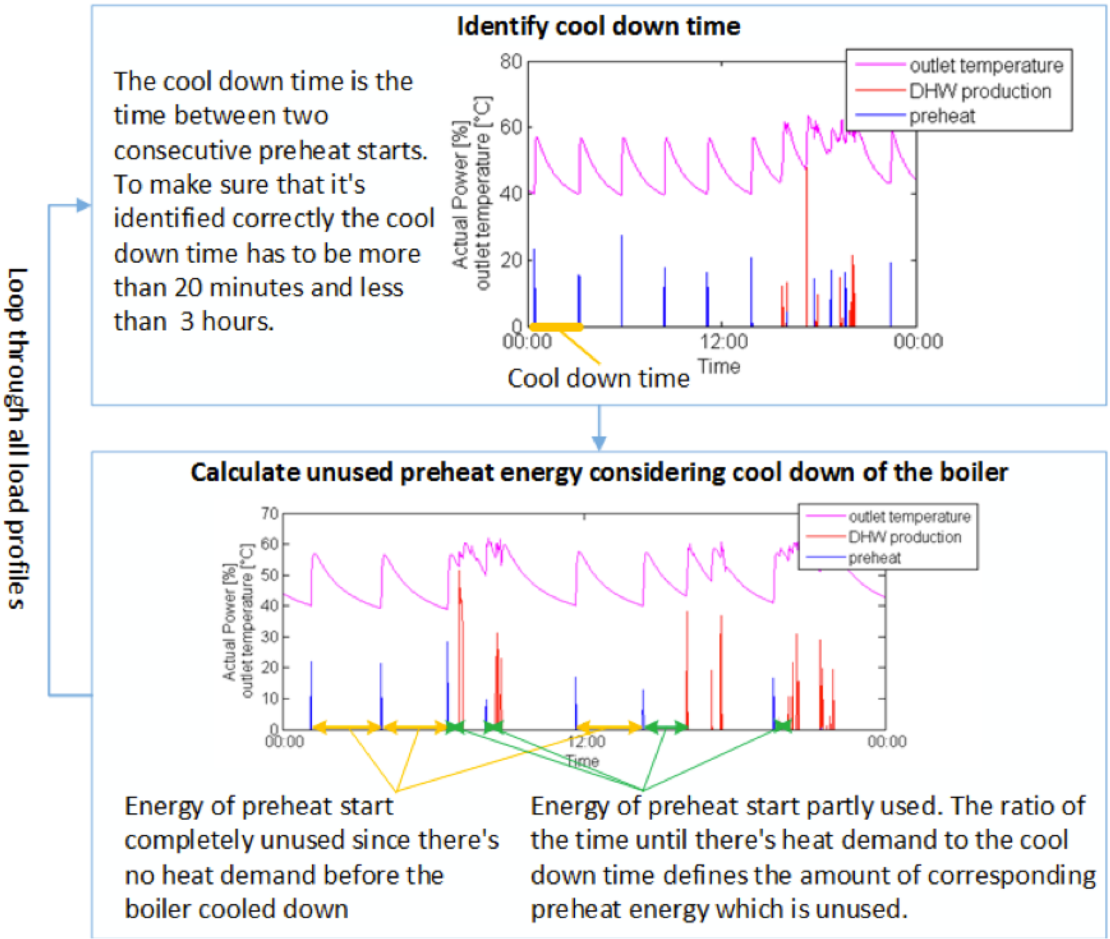


Figure 120: Flow diagram of unused keep-hot preheat energy algorithm (Ramin, 2017)

In the data set, there was no channel recorded which shows whether the keep-hot function is active or not, no functional flag. It is possible that the keep-hot function was switched on and off during the measurement period of this dataset, or that the function was on a timer, so all boilers were processed in the same way in the analysis. It could be that the summation of keep-hot operations includes boilers where the function was only active for part of the measurement period therefore skewing to the lower end of the function's energy demand. Using the above algorithm to extract the unused preheat energy per boiler per year, the resulting histogram is shown in the Figure 121.

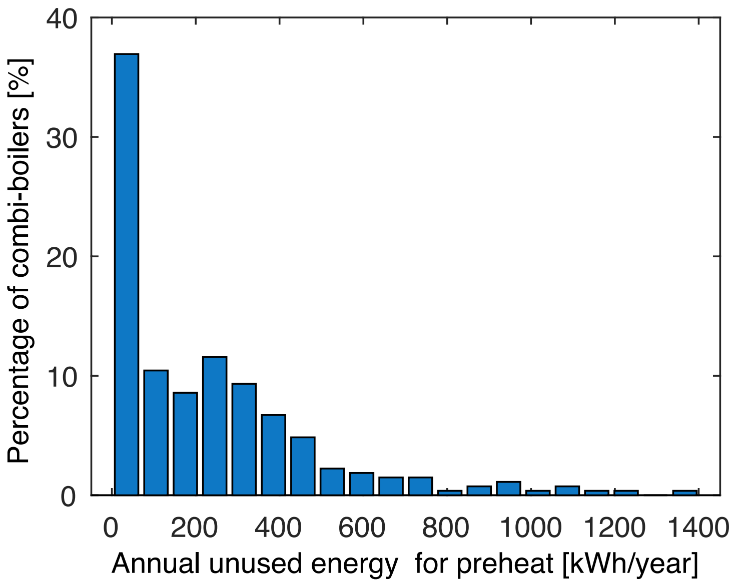


Figure 121: Keep-hot/preheat unused energy per year histogram

Over a third of boilers consumed 60kWh or less per year via the keep-hot function. This could be for a few reasons, such as the keep-hot function being off for most of the time, a timed keep-hot function (possible through more sophisticated dual function time programmers), more regular tappings or longer heating periods. Some boilers also showed cool down periods between keep-hot operations of up to 3 hours: this longer cooling down period would also result in lower losses, with an increased chance of a hot water or heating demand using some of the energy stored in the boiler. The energy loss from the keep-hot function is more in line with the findings from EFUS (DECC, 2014) than the calculation derived default in SAP shown in the table below.

Table 28: Keep-hot function heat loss per year

Reference	Annual Preheat energy demand [kWh/year]
SAP	600 to 900
Energy Follow-Up Survey 2011 (DECC, 2014)	179 to 414
Empirical Dataset B – only keep-hot mode	340 +/- 250

SAP only calls on the default values of 600 (timed) and 900 (untimed) kWh per year if no measurement value from EN13203-2 is available, which would allow manufacturers to implement measures to reduce this rather unnecessary loss of energy in the system. Besides the energy loss, the issue of unnecessary starts occurs again here, maybe more so than in the cases of cycling in space heating mode. An unwanted keep-hot function start not only results in unneeded heat but also creates the short type of boiler start which is associated with higher emissions, both of CO_2 and other more potent greenhouse gases, and can lead to premature wear out of components.

Simply firing the boiler regularly to try and catch a hot water demand by chance is the case for uncontrolled use of the function, as was seen in more detail in UK2 house where the function was active 24/7 before the homeowners noticed and switched the function off. Simple measures could be used to alleviate the problem, such as shipping combi boilers with the function defaulted to OFF, which was not the case for all boilers under consideration here, informal discussions with Worcester Bosch revealed that in recent years the function had been switched from default ON to default OFF in production, although no specific date was given. Such simple measures can be used to nudge behavioural change before considering more expensive solutions such as timed functionality or smart algorithms to learn when best to activate the function (Ramin, 2017).

7 Discussion and conclusions

The scope of this thesis was to investigate the dynamic effects which present themselves in residential heating systems in the UK, and by considering these phenomena, provide insights into in-situ performance of technology which can save energy and carbon. It considered how the installation and controls impact performance, the implications for future heat and how current calculation methods for energy efficiency such as SAP can be improved. With further research the findings can help support policy and practice.

From the literature review it was found that the complexity of factors contributing to boiler systems performance was not represented in standardised efficiency testing or building energy demand assessment. Issues of plant size ratio, boiler modulation and effective heating system control were some of the topics highlighted and found to be candidates for contributory factors to the performance gap. Many of the issues were found to be pertinent to alternative heaters such as heat pumps. With this in mind, the following research questions were formulated to address not only the performance topics themselves but also the methods used to analyse them in the field.

How are the dynamic behaviours of building heating systems represented in the National Calculation methods for EPCs and does this representation lead to inconsistent calculation of space heating and temperatures?

How can high quality heating system diagnostic data contribute to improvements in building heat demand characterisation?

In this discussion section, the aim is to bring together the findings from the various chapters on simulation, case study and data analysis into a more comprehensive narrative, in order to explore to what extent, the questions have been answered. While reviewing, effort will be made to elaborate on the relevance of the topics in the wider context of UK energy demand, both now and into the future.

The literature and industry experience clearly pointed to two key, but complementary, issues regarding boilers which can impact efficient performance. Short and rapid cycling (switching between ON and OFF states) was linked to inefficient performance of boilers. The manner in which dynamic behaviour manifested itself is discussed in section 7.1. Following on from that the additional implications, besides efficiency are elaborated upon in the section on emission covering the hitherto overlooked topic of operational methane emissions from boilers. In section 7.3 the implications for SAP and EPCs will be discussed by linking boiler theory to the simulations and real-world performance to assess the impact on building energy performance assessment of SAP and standardised lab testing/labelling. Finally, the discussion will look from the current heating systems forward to the next generation and the further research that can support in the light of the findings in this thesis.

7.1 Dynamic behaviour of heating systems

Issues with the treatment of heating system dynamics were identified, and oversimplifications in standard testing and in National Calculation methods like SAP highlighted; the challenge was to unpick the mechanics of the relationship in such a way as to make implementation in SAP, and mitigation in the real world, possible.

SAP, the national calculation method of the UK, assumes that a heating system increases the internal temperature instantaneously and maintains the temperature at the desired setpoint perfectly for the duration of the heating schedule. Simulations showed that this, as predicted by the literature (Murphy et al., 2011), is clearly not the case. Heat up time depends on the size of the boiler installed, with boiler sizes matched to building steady state demand (according to standard plant sizing methods) being unable to maintain a consistent internal temperature at the desired setpoint when forced to adhere to the two relatively short daily heating periods (morning and evening) recorded in the literature (Huebner et al., 2013a), and observed in this research. This type of heating schedule represents a low intermittency factor for the heating system which, as has been shown, impacts the performance of the heating system boiler. Variation of the plant size ratio showed that following guidelines (such as those from CIBSE (Butcher, 2005)) to install PSR approaching one may result in internal setpoint temperatures not being met in winter without the use of heat up optimization algorithms. These functions allow the heating system to operate outside of the programmed heating period, or intervention from the occupier. Installer trends to oversize boilers in installations due to a focus on hot water demand (Orr et al., 2009), were confirmed through Dataset A and B.

It is likely that nationally, most boilers are oversized with respect to the building heat load. This may be compounded when the heat emitters are undersized, particularly in older properties or when radiators may not be fully filled with water and require bleeding. Besides providing sufficient power to reach the setpoint room temperature quickly there are practical incentives to manufacturers, installers and consumers to oversize heating systems. However, it is potentially convenient and economic (at the point of installation) to oversize the boiler only, overlooking the radiators, due to their size impact on space use, thereby constructing a mismatched system prone to dysfunctional cycling operation, often operating for less than 10 minutes at a time. If a new heating system fails to heat the property as quickly as the previous system, or reduces the perceived warmth from radiators, then a complaint could potentially be made by the building inhabitant to the installer and, in turn, the manufacturer. Therefore, if heat up time and comfort are potentially perceived to be of greater importance than efficiency, then it is conceivable that consumer pressure would lead to generally oversized boilers. Simulations (Section 5) showed that with increased oversizing, heat demand would rise and efficiency would drop, accompanied by more rapid cycling. Utilising boiler diagnostic data to investigate heating system behaviour in a level of detail and accuracy not normally possible has highlighted performance issues previously undetected in research studies. In the case of combi boilers this was found to be the case with the 217 boiler Dataset B, where boiler output was larger than all but the highest heat demand residential buildings in the UK. Further analysis showed cycling akin to that seen in simulation was present with on-off cycling averaging more than 50 starts per day, with 70% of the cycles lasting less than 10 minutes in space heating operation. The mismatch between a building space heating demand and hot water demand is likely to be a major driving factor of oversizing in residential properties.

Detailed measurement in case study Dataset A, where the building heat loss was estimated from SAP and also PTG measurements, identified such an oversizing bias of combis. It is also worth noting that UK3 and DE1 case study houses are examples of system (non-combi) boilers which were also oversized (albeit to a lesser degree than the observed combis), lending support to the influence of oversizing for thermal comfort responsiveness even in the absence of combi functionality. The root causes or processes that lead to oversized boilers in homes were not apparent from the predominantly technical research presented here, but what is clear from looking at SAP, EPCs and other residential building legislation and labelling is that oversizing is not actively discriminated against for boilers with regards to building control or energy assessment. Therefore, any bias there may be in the minds of consumers, installers or manufacturers to specify boilers that may be too large with regards to building space heating demand can go largely unchecked due to lack of incentives to the contrary and awareness of the performance penalty that will be paid. An exploratory overview of the conceivable forces and pressures at work on the selection, cost, installation and usage of the heating systems is presented in Table 29.

Table 29: Potential conflicting costs and benefits contributing to oversizing

Actor	Advantage of oversizing	Disadvantage of oversizing	Financial effect
Installer	Lower chance of complaint regarding thermal comfort No detailed heat loss calculation necessary Simplified boiler sourcing	Missed opportunity to upgrade radiators	Reduction in unpaid recalls for thermal comfort issues. Time saving from heat loss omission
Householder	Fast space heating Higher DHW flowrate (combi) Installer savings shared Saving of radiator cost	Shortened boiler lifetime from cycling wear Reduced efficiency through cycling	Increased boiler cost: 20-40 £/kW Running costs: 10-15% efficiency decrease
Manufacturer	Simplified product portfolio Lower chance of complaint regarding thermal comfort	Shortened boiler lifetime from cycling wear (Warranty costs)	Approx. £150 callout cost plus part cost Sales loss through low quality perception

Besides the relative size of the boiler to the building heat load, the control type also played an important role in the dynamic control of the boiler modulation and room temperature. Simulations showed that poor feedback mechanisms result in temperature overshoot of 1°C in the scenario considered; adding controlled feedback improves the situation, reducing error to 0.1°C, with the best performance being shown by feedback coupled with controlled modulation of the boiler output temperature. SAP also simplifies the control of the room temperature during the heating period to a near perfect control mechanism. However, the simulations showed the effect of poor control on the internal temperatures of the building, overshoot and eventual increase of the overall mean internal temperature over the heating period. The same building with the same boiler can react significantly differently, thermally, when paired to a different control system. Simple controls were shown to increase internal temperatures by partially negating the modulation ability of the boilers they triggered. Trigger is a more accurate verb than control for these systems, since by operating a thermostatic relay in the living space, the resulting ON/OFF signal to the boiler carries no information as to the temperature deficit to be bridged, meaning that other boiler controls such as flow water setpoint becomes the target to be reached. Indirectly, from the data collected in this research, such controls seem to be still commonplace in the UK. This is significant since it makes clearer the multiple factors that would need to be entwined in a philosophy of harmonious matching of building, heater and control in a well-balanced system.

The dynamic behaviour of oversized boilers is of clear importance in the residential heating space in the UK. It appears to have a number of causes and overlapping mechanisms, discussed up to now. However, the framework which was chosen to analyse the dynamic behaviour was the National Calculation Method behind Energy Performance Certificates, therefore, by focussing on SAP, we can see it overlooks heating system dynamics in 4 important ways:

- Mean internal temperature
- Efficiency
- Cycling
- Emissions

Mean internal temperature

Since SAP derived the building heat loss based on a mean monthly internal/external temperature difference, it is crucial to the calculation robustness that the MIT method accurately represents the heating system parameters that can determine the internal temperature in order to differentiate between high and low performing systems, preferably quantitively but at least qualitatively. The simulation results indicate that there is a significant gap between the mean internal temperature predicted by SAP and that of the dynamic cases: between 0.6 and 1.2°C for a normally sized heating system in this case study (Section 5.1.1). This is expected to be caused by a mixture of poor control and the effect of residual heat in the heating circuit, which is then transferred to the dwelling outside of the programmed heating period, an effect which is not captured by SAP and which only considers building thermal mass (to a certain depth) and not heating system water. This increase in mean internal temperature also resulted in a consequential impact on heat consumption.

Efficiency

After deriving the net building heat loss, SAP then applies an efficiency factor for the heating plant (taken from standardised testing consisting of) in the case of modulating gas boilers, a weighted average of maximum and minimum steady state modulation levels. These are taken from the PCDB (Product Characteristics Database, the repository of boiler efficiency ratings) which in turn uses SEDBUK and more recently ErP and EN standard test methods. The space heating efficiency standards have evolved into a form that is simple and cost effective to implement, which partially accounts for the manner in which they focus on steady state performance rather than any dynamic conditions, as is done for hot water efficiency. SAP, in its current form, additionally applies an efficiency correction factor to all boilers when their efficiency is above a certain threshold (Hayton, 2009) of heating system controls by applying an efficiency penalty to the boiler. From the findings in this research the assumption that the boiler space heating efficiency can be simplified to a steady state measurement independent of building context, or fixed weighted average thereof, can be challenged. All simulations performed used a boiler of the same theoretical efficiency according to the current testing methodology, and yet performed dramatically differently with different output when paired with various houses and controls (Section 5.2 and 5.3). That an internal combustion engine efficiency varies depending on the car and transmission it is coupled with and the way it is driven is at the heart of automotive standardised type testing for fuel efficiency figures (Dalton and Steinhauser, 2015). To compensate for overlooking boiler efficiency variation with building parameters, SAP implements a correction factor to compensate for the observed divergence of individual boiler steady state results and that seen in the field. This research highlights a more quantitative assessment and a link to plant size ratio, boiler size, boiler modulation range and controls, which can more accurately portray boiler heating system efficiency and distinguish good from poor performance potential.

Cycling

Cycling and efficiency are partially linked; increased cycling was always accompanied by decreased efficiency in the simulations carried out, but cycling itself is problematic for gas fired boilers because of the other effects that stem from rapid behaviour of this type. Mechanical and electrical components in boilers have a finite working lifetime. Manufacturers aim to design, test and manufacture the components for the expected lifecycle of the product: this will often be quantified as a certain number of years general operation, or broken down into number of cycles or hours of burner time. In some cases, like the control system of a boiler, this lifetime requirement is stipulated in the EU and national standard, like the 250 000 cycles rational lifetime in EN298 (GSE, 2012a). High numbers of cycles in the field can lead to premature failure of components and therefore lack of function of the boiler, which is problematic for occupants, especially vulnerable persons such as the elderly or infants. The reliability of heating systems is a key factor of the customer satisfaction with a boiler, or any heating system. Reliability is listed highly as a selection criterion from Consumer group 'Which?', and is also mentioned as important by installers to avoid call-backs (Wade et al., 2017). Therefore, increased cycling behaviour that can negatively impact on the lifetime needs to be quantified in order to adapt systems to mitigate cycling or design products with increased robustness. Since cycling is also linked in the research with decreased efficiency then it would be preferable to address boiler and system issues that increase cycling in order to tackle both reliability and efficiency together.

Emissions

ON/OFF cycles during CH operation mode are a potential side effect of the boiler/building/control nexus, but boiler starts in general, whether from CH cycling or normal DHW demand through a combi are also increasing emissions. The high number of boiler starts observed in the wider boiler population (Dataset B) in CH mode is of relevance not only because of the associated drop in efficiency due to the short running times, but also because of an implied increase in methane emissions with their higher greenhouse warming potential. Due to a tradition of steady state testing based on the assumption of optimal sizing of boiler and heating system, legislation is mostly oblivious to these hidden emissions.

DHW tappings will inevitably interrupt CH operation during the heating season for combis without storage capacity due to the requirements to move internal valves and pause burner/pump operation. Therefore, cycling behaviour seen in the simulations is likely to persist, albeit at a reduced level, if CH sizing and modulation are improved to alleviate pure CH cycling. The field results from this study showed the high number of tappings and starts that are prevalent in the UK boiler market, dominated by combis. In summary, SAP considers the CO_2 emissions to fulfil the building heating demand at a full and part load steady state efficiency point. The reality seems to be more complex with emissions of CO_2 being driven also by cycling and modulation dynamics of the boiler system and additional fugitive methane emissions during start being overlooked by SAP and standardized testing.

7.2 Omissions and forgotten emissions

Previous studies of the high start-up emissions of gas boilers indicates that avoidance of cycling behaviour should be a priority for the boiler heating system as a whole. With millions of boilers installed and hundreds of thousands still being installed annually, the identification of any issues in this area and their solution represents an impactful, low hanging fruit in the battle for emissions reduction. So, the high number of starts observed in CH simulation and confirmed in Dataset A and B is of concern, not only because of an associated drop in efficiency due to the short running times, but also because of the implied increase in methane emissions with their higher greenhouse warming potential this compounds the negative trend of efficiency with increasing boiler oversizing and cycling with additional methane emissions. Legislation is mostly oblivious to these hidden emissions due to a tradition of steady state testing and assumed optimal pairing of boiler to heating system. Although the data presented here cannot conclusively identify the causes for poor performance of boilers in UK housing stock, and further research would be recommended to follow up this open point. The reality of the observations is that current legislation such as EN15502 for boiler efficiency or SAP for building performance does not take account of the issue of dynamic behaviour in CH mode. Efficiency is the proxy for carbon dioxide emissions, carbon monoxide and NOx are covered by the standard (also steady state), but methane is overlooked, along with the cycling behaviour that would impact all of the above. Due to the absence of a procedure and limit on which to build, it can be assumed that the situation is unlikely to change in the near future since the real magnitude of the problem is not currently measured.

7.3 Implications for SAP and EPCs

Finding that there are heating system dynamic issues that influence the space heating demand and emissions, but that these are not reliably implemented and represented in SAP, is a cause for concern with regards to current and future EPC usage. To be an effective comparison mechanism for building energy demand, EPCs promise to give a standardised energy demand for a given building that can be used by a potential resident to inform decision making in the market. To do this, SAP standardises the user behaviour, heating schedule and weather. This should allow a fair comparison of the building fabric and heating system. Putting aside the uncertainty of making an EPC (CCC, 2016), the methodology adds further uncertainty by overlooking pertinent parameters which, like the choice of wall insulation or double glazing, will have a definitive effect on energy demand, regardless of user behaviour. From the findings made in this thesis, across simulation and field measurement, it seems that heating system parameters are oversimplified in SAP for the case of boilers. The current SAP method of monthly building heat loss summed over fabric and ventilation multiplied by boiler efficiency to give gas demand has simplified the calculation to an extent to make similar inter house comparisons less informative when the differences are limited to the heating system, which undermines the rest of the EPC comparisons for UK residential housing stock.

The issues outlined earlier in this discussion can be addressed in the SAP methodology without increasing the complexity of SAP, which has a computational efficiency to be admired. Although a move to fully dynamic simulation similar to that used in this research could more fully address the technical aspect of the boiler behaviour and provide increased precision, it is doubtful that, in the hands of time pressurised EPC assessors, it would provide an increase in overall accuracy or regulatory effectiveness (Raslan, 2010). Therefore, by maintaining the simple framework of SAP while adapting or adding parameters the increased accuracy will not be outweighed by complexity or tendency for error. From the research carried out, the plant size ratio is a good candidate for just such an addition. The building heat loss is already calculated in the SAP method, with the addition of the boiler space heating capacity, and potentially modulation range, a PSR would be calculable and linked to an efficiency penalty for the heating system in that building. Boiler space heating size is found on the boiler information plate or literature, with no need for a time-consuming forensic analysis to be carried out. Since the assessor should already determine the make and model of the boiler to extract the efficiency from the PCDB, the boiler output is information they have already collected. This addition to the assessment procedure would allow the SAP calculation to adjust efficiency in line with PSR and boiler minimum modulation and emissions, in line with the cycling propensity. By considering a heating system parameter such as this, it is conceivable manufacturers may be incentivised to focus development on operational efficiency issues and that the SAP method as a whole may also be simplified. Currently there is an adjustment factor applied across all gas boilers, regardless of manufacturer or modulation range, as well as setting an upper practical limit. This is implemented as compensation for the observed under performance of boilers in the field compared with standard tests. But this research offers a more systematic approach, using PSR and modulation, therefore possibly eliminating the current 'one size fits all' approach.

Low temperature systems for condensing boilers and heat pumps are considered in SAP, but evidence of their implementation was not seen in the case studies (Dataset A) and the high average flow temperatures in the boilers analysed (Dataset B) implies that take up of such systems is low. The complexity of the motivation of the various actors in the selection of heating systems plays a role here (Banks, 2000). This is a further reason for placing more emphasis on the PSR and modulation range as a driver for calculation efficiency in SAP, since these are measures which can be implemented at a lower cost and disruption to the occupant, and offer a low effort addition to the EPC assessor. Naturally such an improvement to the accuracy of SAP would not come without a penalty. If future boiler replacements were specified on the basis of a lower PSR then heat up times of the house would lengthen, as seen in the simulations and collected data. This could lead to reduced comfort without adaptation of the control or heating schedule, which may outstrip heating efficiency gains. Although simulation of the heat up optimisation showed little energy or comfort penalty for longer operating times. However, widening of boiler modulation offers a way to decrease the effective PSR in terms of the minimum boiler modulation and therefore the propensity to cycle.

Consideration of the heater, emitters, controls as a holistic system where only certain combinations of elements will operate optimally and as expected. Treatment of controls in isolation will not deliver the expected improvements when considered under the current SAP system. For example, the changing of a control would best be incentivised in such a way as it 'fits' with the existing system and the benefit is calculated accordingly. There is a clear gap in the theory as implemented in SAP's quasi static calculation method relating to heating system specific parameters such as thermal mass, PSR and to a lesser extent control type. Since the BREDEM calculation method is also used for policy evaluation in the UK, the simplification may also disadvantage some technologies from a national policy context. Improvement of the NCM in this area would lead to a more realistic representation of the relative benefits of different heating systems in EPCs. Sharpening of the near ubiquitous EPCs as a policy tool can help to influence the improvement of domestic heating systems in the UK with respect to efficiency and comfort.

This research has found significant differences in emissions and energy use related to how realistic heating systems are modelled by including thermal capacity of the heating system and heating system size; topics which are currently not in EPC calculations. Some of the performance gap between modelled and measured energy performance may be due to both these factors, and that the simplifications in the UK SAP method may not balance the performance trade-offs of some heating systems and their controllers. Field observations showed that the same detrimental dynamic behaviour is present in the majority of boilers supporting an efficiency penalty in SAP, but the current implementation overlooks the underlying mechanism which can be addressed in the installation and could be improved and incentivised in SAP and EPCs. This presents an opportunity to improve the SAP/EPC framework to address the performance gap.

7.4 Implications for current and next generation heating systems

Ensuring that the efficiency influencing dynamics of boilers are well understood and measures are put in place, all the way from product conception, development, production, installation and usage, will not only benefit the potential millions more gas boilers that will be installed in the next years but also lay a firm groundwork for the next generation of technologies that come thereafter, whether they be demanded by the market or enforced through legislation.

Buildings are not technology agnostic, no heating technology can be considered in isolation from the building in which it will operate, although boilers are as close as we may have in today's market place. Boilers, due to differences in functionality (combi versus system), rating and modulation range are not a 'one size fits all' heating technology, and do not operate independently of the environment in which they operate. However, their efficiency variation is not as great as other technologies. As new heating technologies such as heat pumps seek to penetrate the market and compete with gas boilers there are valuable lessons to be learned from the world of boilers, whose heat distribution and emitter systems they will often inherit. Gas condensing boilers may be the current dominant incumbent of the UK heating market, but only recently this title belonged to non-condensing/conventional boilers. At the time of early transition to condensing, before legislation forced the issue, consumers also grappled with the cost/benefit of boiler replacement when faced with the option of the new condensing technology rumour and entrenched beliefs put doubt in the minds about the justification of the extra cost for the efficiency benefit (Banks, 2000). The next choices will not be as slight as the cost and functional difference between standard and high efficiency boilers. At that time, the occupant could expect to use the latter the same way as the former, but only by adjusting heating patterns, flow rates and control strategies could the full efficiency benefit of condensing be unlocked. This has seemingly not happened based on the evidence in this thesis. If the same mismatching persists for newer technologies, more dynamically sensitive to the building and heating system than boilers then a widening of the performance gap for new technologies may emerge.

Some boiler manufacturers are moving to address oversizing issues in combi boilers (Bosch, 2017a), by moving to a wider modulation range compared to the current state of the art of 1:6 (e.g. 2.4 to 24kW compared to 4 to 24kW). Benefits of a higher modulation range should be the ability of the boiler to reduce its heat output in line with the building heat loss throughout the heating season but is especially pertinent in mild winter and seasonal transition days where previously boilers may have reached their lowest output and were forced to cycle. The topic of cycling cannot be solved solely by modulation range, a holistic view of the heating system within the building envelope, and the factors influencing its installation must be considered to improve efficiencies such as emitter sizing and control method.

Currently it is common practice for installers to fit combination boilers based on maximum DHW output with additional safety margin will continue to determine the upper power output of boilers and therefore the move to larger modulation ranges is in keeping with market drivers. However, the benefits will not be visible to consumers prior to purchase, unless the current performance testing regimes change. Currently two appliances could be tested and shown to have the same efficiency label despite large output differences. This is not in itself a problem providing boilers are matched to the building thermal demand, but this is not always the case. Therefore, it can be assumed that the situation is unlikely to change until legislators make efficiency testing procedures that reflect the realities of heating installations.

Heating system installations, whether they are boilers or otherwise, should be subject to the same level of technical rigour to ensure optimum in situ operation and to avoid customer dissatisfaction. The findings in this research show that, even in the case of a robust technology such as boilers, plant size and control are important for efficiency and reliable temperature control but not always optimally implemented in the field. Replacing one item in the heating system, be it boiler or controls, and expecting the full efficiency benefit is unlikely to be a methodology conducive to maximising energy savings. That heating systems are often replaced due to breakdown, or the fear of it, and that planned upgrades on the basis of efficiency gains are less prevalent, means that there is pressure for piecemeal upgrading of the system. Consumers, used to comparatively cheap and easy boiler replacement which, despite carrying an efficiency performance gap in the field of 15-30%, still performs better than the old boiler, may not accept that their next heating system (e.g. HP) will not only replace the boiler, but also the controls and radiators with the possible addition of buffer storage and the loss of living space that may entail. Delaying tackling this issue until new technologies are urgently necessary in residential energy reduction would seem like unnecessary procrastination in light of the findings of this research. The principles of condensing boiler, emitter sizing, modulation increase and suitable controls that can manage the systems in concert are valid today and immediate gains could be made via the continued large number of boilers installed every year, with research improvements to controls and appliances following on later. Consumers' energy bills would benefit from a more holistic approach to heating systems; government action like Boiler Plus (BEIS, 2016) is a welcome move in the right direction and moves the boiler sector forward in ways that support the wider, and future, heating sector.

Investigating the performance of one major component of the heating system, the boiler, identified a wide range of observable behaviour. Further consideration of the heating system in a more holistic manner could reduce operational phenomena that are associated with higher environmental impact, considering the choices made when sizing emitters/boilers, fitting TRVs, setup bypasses, balancing radiators and selecting control strategies. Legislative tools such as performance and emissions testing and scrappage schemes could be improved by looking more broadly at the heating system rather than only one isolated component of it. However, economic consequences should also be considered, mandatory measures which benefit efficiency may result in increased installation costs, which would discourage or delay much needed upgrades to heating systems.

The Microgeneration Certification Scheme which already governs many technologies such as heat pumps and requires declaration of room by room heat loss calculation, offers a direction for new technologies. Maximum heat emitter flow temperature and heater output. Boilers would benefit from this level of forethought but more critically, the industry as a whole could benefit. Currently, and historically, the building industry and specifically the heating system installers have been seen as having sub-standard levels of training and expertise, especially with regards to newer technologies (ElementEnergy, 2017), therefore a scheme which requires higher levels of professionalism from installers in order to meet MCS style requirements for boilers today may help to improve the industry as a whole. Compliance with MCS, as demonstrated through the RHPP scheme, although not perfect (Gleeson et al., 2017), does address issues of emitter oversizing (EST, 2017), intermittency and seasonal performance in more detail and in a way that would be compatible with addressing some of the issues identified in this research. Crucially MCS supports a philosophy of balancing building heat loss, emitter capacity and heat generation performance in a holistic manner. This could in turn compliment an improved SAP methodology by providing firm input criteria on which to penalise mismatched heater/emitter/building combinations, for boilers and future heating technology.

7.5 Summary

The main outcomes of the research centre around the discovery that cycling behaviour of boiler heating systems is fundamentally detrimental to the system efficiency and is common in the observed heating systems. Oversizing of boilers is a significant root cause of cycling, with quantifiable effects on efficiency which go hand in hand with increased cycling. Moving from a simulated PSR of 8.5 to 2 reduced the daily number of cycles from 51 to 19 and carried a 4% efficiency benefit. Mitigation of already installed oversized systems through measures such as smarter controls or optimisation of heating schedule start times can improve the situation but cannot overcome the underlying issue of the systems inability to match current heat demand. From the analysis of real boiler data from the field, it is clear that cycling is present in working heating systems. The combination boilers observed exhibited average cycle times of the order of minutes (70% of boilers with less than 10minutes) which is of the order shown to be of significant impact on efficiency from the simulation analysis. Although oversizing could not be confirmed in the larger Dataset A the thermal output of observed the boilers (24 - 32kW) is well above that required in the majority of UK homes (according to CHM predictions) and supports the tendency for combination boilers to be size according to DHW with little regard for CH demand. From the case studies both cycling and oversizing were observed with average building heat demand falling below the minimum modulation level of the boiler in 3 out of 4 cases, cycle times were correspondingly short with 2 of the case studies exhibiting 90% of CH cycles less than 10minutes.

Since SAP and energy labelling broadly overlooks the dynamic characteristics of boilers in central heating, a move to update such tools with the means to distinguish between boiler system efficiency on the basis of plant size (and therefore the propensity to cycle) would be a actionable outcome of the research. Given than combination boilers have contradictory design goals from the disparate CH and DHW demand power, tackling the continued oversizing at the point of installation is a challenge that could be met through wide modulation ranges and a deeper look at whether maximum flowrates of DHW are used in practice and could be curbed thereby relieving the tension between the CH and DHW demands.

7.6 Further research

Further investigation into the physical causes for the increased MIT and space-heating requirement of the dynamic situation is still required, especially relating to the lower rate of cooling after heating periods, the simulations performed so far could not yet cover a fully representative cross section of buildings or heating system configurations. This is expected to be influenced by the thermal mass size, distribution and condition. In addition to further simulations, the behaviour of heating systems measured in situ in buildings would be required to further investigate the magnitude and nature of these transient effects and their effect on efficiency and comfort. This has been started as part of this research but further investigation into the method of incorporating such results into the existing SAP framework may then improve its accuracy.

Further research is required to more thoroughly characterise the causes of high boiler cycling, the potential mitigation measures that may be taken and how to implement them in the design/installation/usage lifecycle. It is clear that current legislation such as EN15502 and SEDBUK for boiler efficiency or SAP for building performance does not take account of the issue of oversizing and cycling therefore continuing the work here to develop a pragmatic testing regime that can capture enough dynamic efficiency and emission data to give input to EPCs is still necessary.

Future research will benefit from looking at the heating system as a whole and at its operational context; this is needed to quantify the benefits available from reducing cycling. Such research can support legislation and the industry going forward to close the performance gap with respect to boiler-based heating systems. The complexity of heating system operation and control strategies are highlighted by this analysis and further research may address the interfaces of boiler/heater, controller, heating circuit and ultimately occupant in order to better understand the root causes for phenomena such as cycling and to minimise emissions associated with their operation.

8 Bibliography

1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change.

(JCGM), J. C. F. G. I. M. 2008. International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM 3rd edition) JCGM 200:2012 (JCGM 200:2008 with minor corrections).

ANSI 2013. *Thermal environmental conditions for human occupancy,* Atlanta, Ga., Atlanta, Ga. : ASHRAE.

BALCOMB, J. D. 1992. *Passive Solar Buildings*, MT PRess.

BANKS, N. 2000. Lower Carbon Futures : APPENDIX C: THE UK DOMESTIC HEATING INDUSTRY – ACTORS, NETWORKS AND THEORIES. GfK Marketing.

BARTHOLOMEUS, P. 1987. Application of condensing boilers in the Netherlands.

BEIS 2016. Heat in Buildings: Boiler Plus. *In:* BUSINESS, E. A. I. S. (ed.).

BEIS. 2017a. *Digest of UK Energy Statistics (DUKES)* [Online]. Available: https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes [Accessed].

BEIS 2017b. Energy consumption in the UK. *In:* DEPARTMENT FOR BUSINESS, E. I. S. (ed.). National Statistics.

BEIS 2018. Digest of UK Energy Statistics (DUKES): calorific values. *In:* BEIS (ed.).

BEIZAEE, A., ALLINSON, D., LOMAS, K. J., FODA, E. & LOVEDAY, D. L. 2015. Measuring the potential of zonal space heating controls to reduce energy use in UK homes: The case of un-furbished 1930s dwellings. *Energy and Buildings,* 92**,** 29-44.

BEIZAEE, A., LOMAS, K. J. & FIRTH, S. K. 2013. National survey of summertime temperatures and overheating risk in English homes. *Building and Environment,* 65**,** 1-17.

BENNETT, G., ELWELL, C., LOWE, R. & ORESZCZYN, T. 2016. The Importance of Heating System Transient Response in Domestic Energy Labelling. *Buildings,* 6**,** 29.

BMJ 1999. Radiator market stablises with static sales. *Builders Merchants Journal***,** 42.

BOAIT, P. J., FAN, D. & STAFFORD, A. 2011. Performance and control of domestic ground-source heat pumps in retrofit installations. *Energy and Buildings,* 43**,** 1968-1976.

BORDASS, B., LEAMAN, A. & RUYSSEVELT, P. 2001. Assessing building performance in use 5: conclusions and implications. *Building Research & Information,* 29**,** 144-157.

BOSCH. 2009. *Bosch Thermotechnology: Installation Manual Greenstar iJunior 24/28kW* [Online]. Available: https://www.worcester-bosch.co.uk/support/document/download/release/8716115166/12640 [Accessed 18/02/2016 2016].

BOSCH 2013. Bosch plans residential CHP field trial for 2014. *Fuel Cells Bulletin,* 2013**,** 1.

BOSCH. 2015a. *Bosch Thermotechnology: Installation Manual Greenstar i 25/30kW* [Online]. Available: https://www.worcester-bosch.co.uk/products/boilers/directory/greenstar-i [Accessed 18/02/2016 2016].

BOSCH. 2015b. *Bosch Thermotechnology: Installation manual of Highflow boiler* [Online]. Available: https://www.worcester-bosch.co.uk/products/boilers/directory/greenstar-cdi-highflow [Accessed 9/10/17 2017].

BOSCH. 2017a. *Bosch Thermotechnology: Cerapur 9000i Gas Brennwertheizung (Gas condensing boiler)* [Online]. Bosch Thermotechnology. Available: https://www.junkers.com/endkunde/produkte/produktinformation/produktkatalog_63552 [Accessed 27/11/2017 2017].

BOSCH. 2017b. *Worcester Bosch Heating Controls Specifications* [Online]. Bosch Thermotechnology. Available: https://www.worcester-bosch.co.uk/professional/support/documents/worcester-controls-specification-document [Accessed 20/04/2016 2016].

BOSCH. 2017c. *Worcester Bosch homepage* [Online]. Bosch Thermotechnology. Available: https://www.worcester-bosch.co.uk/ [Accessed 27/11/2017 2017].
BOSCH. 2018a. *Bosch Thermotechnology: Worcester Wave Smart Thermostat* [Online]. Bosch Thermotechnology. Available: https://www.worcester-bosch.co.uk/professional/products/boiler-controls/wave-smart-control [Accessed 29/01/2018 2018].
BOSCH. 2018b. *Greenstar Boiler range* [Online]. Available: https://www.worcester-bosch.co.uk/products/boilers#combi [Accessed 07/09/2018 2018].
BOSCH. 2018c. *Greenstore LECP Heat Pump range* [Online]. Available: https://www.worcester-bosch.co.uk/products/heat-pumps/directory/greenstore-lecp-heat-pumps [Accessed 7/09/2018 2018].
BOSCH. 2018d. *Public Image Library* [Online]. Available: https://www.worcester-bosch.co.uk/professional/support/image-library/system-diagrams [Accessed 31/08/2018 2018].
BOSSCHAERTS, W., VAN RENTERGHEM, T., HASAN, O. A. & LIMAM, K. 2017. Development of a Model Based Predictive Control System for Heating Buildings. *Energy Procedia,* 112**,** 519-528.
BOURKE, G., BANSAL, P. & RAINE, R. 2014. Performance of gas tankless (instantaneous) water heaters under various international standards. *Applied Energy,* 131**,** 468-478.
BRAGER, G. S. & DE DEAR, R. J. 2008. *Historical and Cultural Influences on Comfort Expectations,* Oxford, UK, Oxford, UK: Blackwell Publishing Ltd.
BRAND, S. 1997. *How buildings learn : what happens after they're built,* London, London : Phoenix Illustrated.
BRE 2010. The Government's Standard Assessment Procedure for Energy Rating of Dwellings 2009 edition incorporating RdSAP 2009. *SAP 2009.* Garston, Watford WD25 9XX: BRE.
BRE 2012. SAP Appendix Q database.
BRE 2014. The Government's Standard Assessment Procedure for Energy Rating of Dwellings 2012 edition. *SAP-2012_9-92.* Garston, Watford, WD25 9XX: BRE.
BRE 2016. Consultation Paper – CONSP:02
SAP heating efficiency calculation for condensing boilers
Issue 1.1.
BRE 2017. Product Characteristics Database (PCDB).
BUDERUS-HEIZTECHNIK GMBH, W. 2002. *Handbuch für Heizungstechnik :[Zahlen und Fakten Arbeitshilfe für die tägliche Praxis],* Berlin [u.a.], Beuth.
BUTCHER, K. E., CRAIG, B. E., BUTCHER, K. J. & ENGINEERS, C. I. O. B. S. 2015. *Environmental design : CIBSE guide A / editors: Ken Butcher, Bonnie Craig*, London : Chartered Institution of Building Services Engineers.
BUTCHER, K. J. 2005. CIBSE Guide B - Heating, Ventilating, Air Conditioning and Refrigeration. CIBSE.
BUTLER, D. & DENGEL, A. 2013. Review of co heating test methodologies.
CARBONTRUST 2011. Carbon Trust 2011 Micro chp accelerator final report.
CCC 2016. Next steps for UK heat policy. Committee on Climate Change.
CEN 2008. EN ISO 13790 2008-09 Energy performance of buildings -Calculation of energy use for space heating and cooling (ISO 13790:2008).
CEN 2015a. EN 13203-2 2015-08 Gas-fired domestic appliances producing hot water – Part 2: Assessment of energy consumption.
CEN 2015b. EN 15502-1 2015-10 Gasfired heating boilers – Part 1: General requirements and tests.
CHABOT, C., STOLTE, C. & HANRAHAN, P. 2003. Tableau Software. *Tableau Software*.
CHAMBERS, J. D. 2017. Developing a rapid, scalable method of thermal characterisation for UK dwellings using smart meter data. UCL (University College London).
CHAPMAN, J. 1991. Data Accuracy and model reliability. *Proceedings of Building Energy Performance.* Canterbury, UK.

CHAPMAN, P. F. 1990. The Milton Keynes Energy Cost Index. *Energy and Buildings,* 14**,** 83-101.
CHIU, L. F., LOWE, R., RASLAN, R., ALTAMIRANO-MEDINA, H. & WINGFIELD, J. 2014. A socio-technical approach to post-occupancy evaluation: interactive adaptability in domestic retrofit. *Building Research & Information,* 42**,** 574-590.
CIBSE 2015. *Environmental design : CIBSE guide A / editors: Ken Butcher, Bonnie Craig*, London : Chartered Institution of Building Services Engineers.
CLARKE, J. A. & YANESKE, P. P. 2009. A rational approach to the harmonisation of the thermal properties of building materials. *Building and Environment,* 44**,** 2046-2055.
COMBE, N., HARRISON, D., DONG, H., CRAIG, S. & GILL, Z. 2011. Assessing the number of users who are excluded by domestic heating controls. *International Journal of Sustainable Engineering,* 4**,** 84-92.
CORRADO, V. & FABRIZIO, E. 2007. Assessment of building cooling energy need through a quasi-steady state model: Simplified correlation for gain-loss mismatch. *Energy and Buildings,* 39**,** 569-579.
CRAWLEY, D. B., HAND, J. W., KUMMERT, M. & GRIFFITH, B. T. 2008. Contrasting the capabilities of building energy performance simulation programs. *Building and Environment,* 43**,** 661-673.
DA SILVA, P. & KNABE, G. 2003. LabHouse: System simulation and emulation within boiler development. *Building Services Engineering Research & Technology,* 24**,** 281-287.
DALTON, M. & STEINHAUSER, G. 2015. EU Embraces Real-World Testing --- Governments to start monitoring emissions from cars on the road in wake of VW scandal. Brussels.
DANTER, E. 1951. A survey of Temperatures in Houses. *The Heating and Ventilating Engineer and Journal of Air conditioning*.
DATA-AHEAD. 2017. *Weblogger Case Study* [Online]. Available: https://www.dataahead.de/en/case-studies/worldwide-field-testing-case-study/ [Accessed 1/01/2018 2017].
DAY, A. R., RATCLIFFE, M. S. & SHEPHERD, K. J. 2008. *Types of Boiler and Their Needs,* Oxford, UK, Oxford, UK: Blackwell Science Ltd.
DCLG 2007. English House Condition Survey.
DCLG 2009. English Housing Survey Housing Stock Summary Statistics Tables, 2009, p. SST6.2. *In:* GOVERNMENT, D. F. C. A. L. (ed.).
DCLG 2010. UK domestic building compliance guide 2010. *In:* GOVERNMENT, C. A. L. (ed.).
DCLG. 2014. *Energy Performance of Buildings Certificates: notes and definitions* [Online]. gov.uk. Available: https://www.gov.uk/guidance/energy-performance-of-buildings-certificates-notes-and-definitions [Accessed 29.09.2015].
DCLG 2017. English Housing Survey 2015 to 2016: headline report. *In:* GOVERNMENT, D. F. C. A. L. (ed.) *English Housing Survey.* 2 March 2017 ed.
DE PAEPE, M., T'JOEN, C., HUISSEUNE, H., VAN BELLEGHEM, M. & KESSEN, V. 2013. Comparison of different testing methods for gas fired domestic boiler efficiency determination. *Applied Thermal Engineering,* 50**,** 275-281.
DE WILDE, P. 2014. The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction,* 41**,** 40-49.
DECC 2009. Standard Assessment Procedure for Energy Rating of Dwellings 2009 edition incorporating RdSAP 2009. *SAP 2009 version 9.90.* BRE.
DECC 2012. Standard Assessment Procedure for Energy Rating of Dwellings SAP 2012. *SAP 2012 version 9.92.* BRE.
DECC 2014. Energy Follow-Up Survey (EFUS): 2011.
DECC. 2016. *National Energy Efficiency Data-Framework (NEED) report: summary of analysis 2016* [Online]. Available: https://www.gov.uk/government/statistics/national-energy-efficiency-data-framework-need-report-summary-of-analysis-2016 [Accessed].
DELORME, BRAMHALL, SAMUEL, MCCRYSTAL & HUGHES 2012. EPDB Implementation CA3 National 2012 UK.

DEURINCK, M., SAELENS, D. & ROELS, S. 2012. Assessment of the physical part of the temperature takeback for residential retrofits. *Energy and Buildings,* 52**,** 112-121.
DEUTSCHERMIETERBUND. 2017. *Mietvertrag* [Online]. Deutscher Mieterbund e.V. Available: http://www.mieterbund.de/service/mietvertrag.html [Accessed 9/10/2017 2017].
DIN 2011a. DIN V 18599-1 2011-12 Energy efficiency of buildings - Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting – Part 1: General balancing procedures, terms and definitions, zoning and evaluation of energy sources. DIN.
DIN 2011b. DIN V 18599-2 2011-12 Energy efficiency of buildings – Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting – Part 2: Net energy demand for heating and cooling of building zones.
DIN 2012. DIN 4701-10 A1 2012-07 Energy efficiency of heating and ventilation systems in buildings –
Part 10: Heating, domestic hot water supply, ventilation; Amendment A1.
EC 2013a. COMMISSION DELEGATED REGULATION (EU) No 811/2013 ENERGY LABELLING: supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to the energy labelling of space heaters, combination heaters, packages of space heater, temperature control and solar device and packages of combination heater, temperature control and solar device. *In:* EU (ed.) *(EU) No 811/2013.* Official Journal of the European Union.
EC 2013b. COMMISSION REGULATION (EU) No 813/2013 of 2 August 2013 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for space heaters and combination heaters. *In:* EC (ed.) *No 813/2013.* Official Journal of the European Union.
EC 2014. A policy framework for climate and energy in the period from 2020 to 2030 COM(2014) 15 final. European Commission.
EEA 2016. Explaining Road Transport Emissions. A Non-technical Guide. EEA.
ELEMENTENERGY 2017. Hybrid Heat Pumps Final Report. BEIS: BEIS.
ELWELL, C. A., BIDDULPH, P., LOWE, R. & ORESZCZYN, T. 2015. Determining the impact of regulatory policy on UK gas use using Bayesian analysis on publicly available data. *Energy Policy,* 86**,** 770-783.
ENERGIEFACHBERATE.DE. 2016. *Stoßlüften: So lange sollten Hausbesitzer wirklich lüften* [Online]. Available: http://www.energie-fachberater.de/heizung-lueftung/lueftung-klima/lueftung/stosslueften-so-lange-sollten-hausbesitzer-wirklich-lueften.php [Accessed].
EPBD 2002. Directive 2002/91/EC of the European Parilament and of the Council of 16 December 2002
on the energy performance of buildings. *In:* PARLIAMENT, E. (ed.). Official Journal of the European Communities.
EPBD 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010
on the energy performance of buildings. *In:* PARLIAMENT, E. (ed.). Official Journal of the European Communities.
EST 2001. Controls for domestic central heating and hot water– guidance for specifiers and installers. *Energy efficiency best practise in housing: GOOD PRACTICE GUIDE,* 302.
EST 2010. Getting warmer a field trial of heat pumps report. *In:* ENERGYSAVINGSTRUST (ed.).
EST 2017. MIS 3005 Heat Emitter Guide for Domestic Heat Pumps. DECC.
EST, E. S. T. 2008. Measurement of Domestic Hot Water Consumption in Dwellings. Energy Saving Trust.
EUROSTAT 2013. Final energy consumption in households by fuel. *In:* EUROSTAT (ed.).
FANGER, P. O. 1972. New York, New York : McGraw-Hill.

FARMER, D., JOHNSTON, D. & MILES-SHENTON, D. 2016. Obtaining the heat loss coefficient of a dwelling using its heating system (integrated coheating). *Energy & Buildings,* 117**,** 1-10.
FELS, M. F. 1986. PRISM: An introduction. *Energy and Buildings,* 9**,** 5-18.
FELSMANN, C., KRIENER, K. & KNABE, G. 2000. *Validierung des Simulationsmodells der Robert Bosch GmbH.* Abschlussbericht, TU Dresden.
FIALA, D., LOMAS, K. J. & STOHRER, M. 1999. A computer model of human thermoregulation for a wide range of environmental conditions: the passive system. *Journal of applied physiology (Bethesda, Md. : 1985),* 87**,** 1957.
GIAKOUMIS, E. G. & ZACHIOTIS, A. T. 2018. Comparative evaluation of eight legislated driving schedules in terms of cycle metrics and emissions from a diesel-powered turbocharged van. *Transportation Research Part D,* 58**,** 139-154.
GLEESON, C., BIDDULPH, P., LOWE, R., LOVE, J., SUMMERFIELD, A., OIKONOMOU, E., WINGFIELD, J. & MARTIN, C. 2017. Analysis of Heat Pump data from the Renewable Heat Premium Payment Scheme (RHPP) to the Department of Business, Energy and Industrial Strategy: Compliance with MCS Installation Standards. UCL.
GLEESON, C. P. 2014. Understanding the field performance of domestic heat pumps: an analysis of recent residential heat pump field trials and training needs. *In:* LOWE, R. (ed.). UCL (University College London).
GLEESON, C. P. 2015. Residential heat pump installations: the role of vocational education and training. *Building Research & Information***,** 1-13.
GRAM-HANSSEN, K. 2010. Residential heat comfort practices: understanding users. *Building Research & Information,* 38**,** 175-186.
GRATZL-MICHLMAIR, M., GRAF, C. & GOERTH, A. 2012. Vergleichsberechnung eines Energieausweises nach deutschen und österreichischen Algorithmen. *Bauphysik,* 34**,** 286-291.
GREEN, R. 2012. The effects of cycling on heat pump performance. EA TEchnology.
GREENING, GREENE, DIFIGLIO & CARMEN 2000. Energy efficiency and consumption — the rebound effect — a survey. *Energy Policy,* 28**,** 389-401.
GSE 2012a. *BS EN 298:2012 - Automatic burner control systems for burners and appliances burning gaseous or liquid fuels*.
GSE 2012b. BS EN 15502-1:2012+A1:2015 - Gas-fired heating boilers. General requirements and tests. *DE version: Heizkessel fur gasförmige Brennstoffe. Allgemeine Anforderungen und Prüfungen.*
HAM, J. & DUBBELD, H. 1985. Performance of High-Efficiency Gas Boilers. *Batiment International, Building Research and Practice,* 13**,** 85-93.
HANSEN, E. G. 1985. *Hydronic system design and operation : a guide to heating and cooling with water,* New York ; London, New York ; London : McGraw-Hill.
HAYTON, J. 2009. STP09-B05 Meta-analysis of boiler test results. *Technical Papers supporting SAP2009.* BRE.
HENDERSON, J. & HART, J. 2012. BREDEM 2012 specification.
HESELTON, K. E. 1998. Cycling Efficiency: A Basis for Replacing Outsized Boilers. *Energy Engineering,* 95**,** 32-44.
HHWT 2010a. Heating and Hot Water Pathways to 2020. *In:* LTD, P. M. R. (ed.). HHWT, Heating and Hot Water Taskforce.
HHWT, H. A. H. W. T. 2010b. Heating and Hot Water Pathways to 2020. *In:* LTD, P. M. R. (ed.).
HIRST, E., WHITE, D. & GOELTZ, R. 1985. Indoor temperature changes in retrofit homes. *Energy,* 10**,** 861-870.
HITCHIN, E. R. 1979. The sizing of heating systems for well-insulated houses. *Applied Energy,* 5**,** 277-295.
HMGOVERNMENT 2018. Approved Document L1B: conservation of fuel and power in existing dwellings, 2010 edition (incorporating 2010, 2011, 2013, 2016 and 2018 amendments). HM Government.

HOUWING, M., AJAH, A. N., HEIJNEN, P. W., BOUWMANS, I. & HERDER, P. M. 2008. Uncertainties in the design and operation of distributed energy resources: The case of micro-CHP systems. *Energy,* 33**,** 1518-1536.

HUEBNER, G. M., MCMICHAEL, M., SHIPWORTH, D., SHIPWORTH, M., DURAND-DAUBIN, M. & SUMMERFIELD, A. 2013a. Heating patterns in English homes: Comparing results from a national survey against common model assumptions. *Building and Environment,* 70**,** 298-305.

HUEBNER, G. M., MCMICHAEL, M., SHIPWORTH, D., SHIPWORTH, M., DURAND-DAUBIN, M. & SUMMERFIELD, A. 2013b. The reality of English living rooms – A comparison of internal temperatures against common model assumptions. *Energy and Buildings,* 66**,** 688-696.

HUGHES, POPE, PALMER & ARMITAGE 2016. UK Housing Stock Models Using SAP: The Case for Heating Regime Change. *Science Journal of Energy Engineering,* 4**,** 10.

HUGHES, M., POPE, P. & PALMER, J. 2011. Cambridge Housing Model (DECC).

HUGHES, T. 2011. *Class action lawsuit against LEED and USGBC evolves* [Online]. Washington Business Journal. Available: https://www.bizjournals.com/washington/blog/2011/02/class-action-lawsuit-against-leed-and.html [Accessed 28/06/2018 2018].

HUNT, D. V. L. & ROGERS, C. D. F. 2014. A Benchmarking System for Domestic Water Use. *Sustainability,* 6**,** 2993-3018.

IISD. 2015. *UN Climate Change Conference in Paris* [Online]. Available: http://enb.iisd.org/climate/cop21/ [Accessed 10/09/2018 2018].

IMMOTICKET24GMBH. 2018. *Energieausweis online erstellen* [Online]. Immoticket24.de GmbH. Available: https://www.energieausweis-online-erstellen.de/ [Accessed 10/09/2018 2018].

JOHNSTON, D., LOWE, R. & BELL, M. 2005. An exploration of the technical feasibility of achieving CO 2 emission reductions in excess of 60% within the UK housing stock by the year 2050. *Energy Policy,* 33**,** 1643-1659.

JOHNSTON, D., MILES-SHENTON, D. & FARMER, D. 2015. Quantifying the domestic building fabric 'performance gap'. *Building Services Engineering Research and Technology,* 36**,** 614-627.

JOKISALO, J. & KURNITSKI, J. 2007. Performance of EN ISO 13790 utilisation factor heat demand calculation method in a cold climate. *Energy and Buildings,* 39**,** 236-247.

JONES, D., PE 2014. Principals of Condensing Boiler System Design. *ASHRAE Transactions; Atlanta,* 120**,** 8.

KELLY, S., CRAWFORD-BROWN, D. & POLLITT, M. G. 2012. Building performance evaluation and certification in the UK: Is SAP fit for purpose? *Renewable and Sustainable Energy Reviews,* 16**,** 6861-6878.

KIM, Y.-J., YOON, S.-H. & PARK, C.-S. 2013. Stochastic comparison between simplified energy calculation and dynamic simulation. *Energy and Buildings,* 64**,** 332-342.

KINGMA, B. R., FRIJNS, A. J., SCHELLEN, L. & VAN MARKEN LICHTENBELT, W. D. 2014. Beyond the classic thermoneutral zone: Including thermal comfort. *Temperature,* 1**,** 142-149.

KLEIN, S. A., BECKMAN, W. A. & DUFFIE, J. A. 2010. TRNSYS 17: A Transient System Simulation Program. Madison, USA: Solar Energy Laboratory, University of Wisconsin.

KOKOGIANNAKIS, G., KOKOGIANNAKIS, P. & STRACHAN, J. 2008. Comparison of the simplified methods of the ISO 13790 standard and detailed modelling programs in a regulatory context. *Journal of building performance simulation,* 1**,** 209-219.

LENT, R. 2016. Evaluating the cooling and computing energy demand of a datacentre with optimal server provisioning. *Future Generation Computer Systems,* 57**,** 1-12.

LI, F. G. N., SMITH, A. Z. P., BIDDULPH, P., HAMILTON, I. G., LOWE, R., MAVROGIANNI, A., OIKONOMOU, E., RASLAN, R., STAMP, S., STONE, A., SUMMERFIELD, A. J., VEITCH, D., GORI, V. & ORESZCZYN, T. 2014. Solid- wall U -values: heat flux measurements compared with standard assumptions. *Building Research & Information***,** 1-15.

LOMAS, K. J. & EPPEL, H. 1992. Sensitivity analysis techniques for building thermal simulation programs. *Energy and Buildings,* 19**,** 21-44.
LOMAS, K. J., EPPEL, H., MARTIN, C. J. & BLOOMFIELD, D. P. 1997. Empirical validation of building energy simulation programs. *Energy and Buildings,* 26**,** 253-275.
LOWE, R. 2007. Technical options and strategies for decarbonizing UK housing. *Building Research & Information,* 35**,** 412-425.
LOWE, R., CHIU, L. F., OIKONOMOU, E., GLEESON, C., LOVE, J., WINGFIELD, J. & BIDDULPH, P. 2017a. Case Studies Report from the RHPP Heat Pump Monitoring Campaign. *Analysis of data from Heat Pumps installed cia the Renuewable Heat Premium Payment Scheme.* UCL Energy Institute.
LOWE, R., SUMMERFIELD, A., OIKONOMOU, E., LOVE, J., BIDDULPH, P., GLEESON, C., CHIU, L.-F. & WINGFIELD, J. 2017b. Detailed analysis of data from heat pumps installed via the Renewable Heat Premium Payment Scheme (RHPP). UCL.
LOWE, R., WINGFIELD, J., BELL, M. & BELL.J. 2007. Evidence for heat losses via party wall cavities in masonry construction. *Building Services Engineering Research and Technology,* 28**,** 161-181.
LOWE, R. J., CHIU, L. F. & ORESZCZYN, T. 2017c. Socio-Technical Case Study Method in Building Performance Evaluation. *Building Research & Information,* 45.
MCMAHON, R., SANTOS, H. & MOURÃO, Z. S. 2017. Practical considerations in the deployment of ground source heat pumps in older properties—A case study. *Energy and Buildings*.
MENEZES, A. C., CRIPPS, A., BOUCHLAGHEM, D. & BUSWELL, R. 2012. Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. *Applied Energy,* 97**,** 355-364.
MIARA, M., GÜNTHER, D., KRAMER, T., OLTERSDORF, T. & WAPLER, J. 2011. Wärmepumpen Effizienz: Messtechnische
Untersuchung von Wärmepumpenanlagen zur Analyse und Bewertung der Effizienz im realen Betrieb. Freiburg: Fraunhofer-Institut für Solare Energiesysteme
ISE.
MITAL, A., DESAI, A., SUBRAMANIAN, A. & MITAL, A. 2014. 2 - Developing Successful Products. *Product Development (Second Edition).* Oxford: Elsevier.
MURPHY, G. 2012. *Inverse Dynamics based Energy Assessment and Simulation / Gavin Bruce Murphy.*, Strathclyde.
MURPHY, G. B., KUMMERT, M., ANDERSON, B. R. & COUNSELL, J. 2011. A comparison of the UK Standard Assessment Procedure and detailed simulation of solar energy systems for dwellings. *Journal of Building Performance Simulation,* 4**,** 75-90.
MYHRE, G., SHINDELL, D., BRÉON, F.-M., COLLINS, W., FUGLESTVEDT, J., HUANG, J., KOCH, D., LAMARQUE, J.-F., LEE, D., MENDOZA, B., NAKAJIMA, T., ROBOCK, A., STEPHENS, G., TAKEMURA, T. & ZHANG, H. 2013. Anthropogenic and Natural Radiative Forcing. *In:* STOCKER, T. F., QIN, D., PLATTNER, G.-K., TIGNOR, M., ALLEN, S. K., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY, P. M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
NATIONALGRID. 2018. *Natural Gas Calorific Value (CV)* [Online]. Available: https://www.nationalgrid.com/uk/gas/market-operations-and-data/calorific-value-cv [Accessed 31.08.2018 2018].
NAVETAS. 2017. *Loop Energy Saver Homepage* [Online]. Available: https://www.loopenergysaver.com/ [Accessed 1/01/2018 2018].
NEFIT. 2015. *Nefit Historie* [Online]. Available: http://www.nefit.nl/consument/over_nefit/historie/historie [Accessed 07/10/2015].
NEFIT. 2017. *Nefit Proline Ketel(Boiler)* [Online]. Available: https://www.nefit.nl/consument/producten/categorieoverzicht_719 [Accessed 16/11/2017 2017].

ODPM 2005. *The Building Act 1984 Amendments to Approved Document L1 : conservation of fuel and power in dwellings / Office of the Deputy Prime Minister,* London, London : TSO.

OPENTHERM. 2017. *OpenTherm Association* [Online]. Available: https://www.opentherm.eu/ [Accessed 14/12/2017 2017].

ORCHARD, W. 2014. Making the most of CHP. *CIBSE Journal,* April**,** 40-43.

ORESZCZYN, T. The energy duality of conservatory use. 3rd European conference on architecture: solar energy in architecture and planning, 17–21 May 1993 Florence, Italy.

ORR, G., LELYVELD, T. & BURTON, S. 2009. Final Report: In-situ monitoring of efficiencies of condensing boilers and use of secondary heating. GASTEC.

PALMER, J., TILLSON, A. & ARMITAGE, P. 2013. Comparing the Cambridge Housing Model against the National Energy Efficiency Data-Framework and Meter Readings.

PERRIN, P. 2012. *Simulationsbasierte Analyse der Einflussfaktoren auf Betriebszahlen von Wärmepumpenanlagen.* PhD, Technischen Universität Carolo-Wilhelmina zu Braunschweig.

PFEIFFER, STRUSCHKA, VON LEPEL & BAUMBACH 1999. Start- und Stoppemissionen von Öl- und Gasfeuerungen Wärmetechnik 5. *Heiztechnik*.

PICKUP & MILES 1977a. The performance of domestic wet heating systems in contemporary and future housing.

PICKUP, G. & MILES, A. 1977b. The performance of domestic wet heating systems in contemporary and future housing.

PICKUP, M. 1977. The performance of domestic wet heating systems in contemporary and future housing.

PRÍVARA, S., ŠIROKÝ, J., FERKL, L. & CIGLER, J. 2011. Model predictive control of a building heating system: The first experience. *Energy & Buildings,* 43**,** 564-572.

PÉREZ-LOMBARD, L., ORTIZ, J., GONZÁLEZ, R. & MAESTRE, I. R. 2009. A review of benchmarking, rating and labelling concepts within the framework of building energy certification schemes. *Energy and Buildings,* 41**,** 272-278.

RAMIN, J. 2017. *Analysis of Boiler diagnostic data from the field to establish heating and hot water patterns, energy consumption trends and user groups* Masters, University of Stuttgart.

RASLAN, R. M. S. 2010. Performance based regulations: the viability of the modelling approach as a methodology for building energy compliance demonstration. UCL (University College London).

RIDDOCH, F. 2012. ene.field residential fuel cell micro-CHP trial begins in Europe. *Fuel Cells Bulletin*, 10//, p.10.

ROSENOW, J. & GALVIN, R. 2013. Evaluating the evaluations: Evidence from energy efficiency programmes in Germany and the UK. *Energy and Buildings,* 62**,** 450-458.

RYSANEK, A. M. & CHOUDHARY, R. 2012. A decoupled whole-building simulation engine for rapid exhaustive search of low-carbon and low-energy building refurbishment options. *Building and Environment,* 50**,** 21-33.

SANCHEZ, N. & MAYS, D. C. 2015. Effect of methane leakage on the greenhouse gas footprint of electricity generation. *Climatic Change,* 133**,** 169-178.

SCHETTLER-KÖHLER, H.-P. 2012. EPDB Implementation CA3 National 2012 Germany.

SCHISCHKE, K., HAGELÜKEN, M. & STEFFENHAGEN, G. 2007. An Introduction to EcoDesign Strategies- Why, what and how?

SCHWEIKER, M., KINGMA, B. R. M. & WAGNER, A. 2017. Evaluating the performance of thermal sensation prediction with a biophysical model. *Indoor Air,* 27**,** 1012-1021.

SHIPWORTH, M., FIRTH, S. K., GENTRY, M. I., WRIGHT, A. J., SHIPWORTH, D. T. & LOMAS, K. J. 2010. Central heating thermostat settings and timing: building demographics. *Building Research & Information,* 38**,** 50-69.

SHORROCK, L. 2009. SAP STP09-DHW01 Analysis of EST DHW data. BRE.

SIT. 2018. *SIT 848 Gas Valve specification* [Online]. Available: http://www.sitgroup.it/wp-content/uploads/2017/08/848-SIGMA-GB.pdf [Accessed].

SIVIOUR, J. 1981. Experimental thermal calibration of houses. *Rapid Thermal Calibration of Houses; Everett, R., Ed.; Technical Report ERG,* 55.

SONDEREGGER, R. C., CONDON, P. E. & MODERA, M. P. 1980. *In-situ measurements of residential energy performance using electric co-heating*, ; California Univ., Berkeley (USA). Lawrence Berkeley Lab.

STAMP, S. 2015. *Assessing uncertainty in co-heating tests: Calibrating a whole building steady state heat loss measurement method.* PhD, UCL (University College London).

STAMP, S., LOWE, R. & ALTAMIRANO, H. 2013. An Investigation Into the Role of Thermal Mass on the Accuracy of Co-heating Tests Through Simulations and Field Results. *IBPSA Building Simulation 2013.* Chambery, France.

SUMMERFIELD, A. J., LOWE, R. J. & ORESZCZYN, T. 2010. Two models for benchmarking UK domestic delivered energy. *Building Research & Information,* 38**,** 12-24.

SUMMERFIELD, A. J., ORESZCZYN, T., HAMILTON, I. G., SHIPWORTH, D., HUEBNER, G. M., LOWE, R. J. & RUYSSEVELT, P. 2015. Empirical variation in 24-h profiles of delivered power for a sample of UK dwellings: Implications for evaluating energy savings. *ENERGY AND BUILDINGS , 88 193 - 202. (2015).*

SUNIKKA-BLANK, M. & GALVIN, R. 2012. Introducing the prebound effect: the gap between performance and actual energy consumption. *Building Research & Information,* 40**,** 260-273.

SWAN, L. G. & UGURSAL, V. I. 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews,* 13**,** 1819-1835.

SØRENSEN, B. 2009. Energy use by Eem Neanderthals. *Journal of Archaeological Science,* 36**,** 2201-2205.

TALEGHANI, M., TENPIERIK, M., KURVERS, S. & VAN DEN DOBBELSTEEN, A. 2013. A review into thermal comfort in buildings. *Renewable and Sustainable Energy Reviews,* 26**,** 201-215.

THERMOSS. 2017. *THERMOSS H2020 Project Homepage* [Online]. Available: https://thermoss.eu/ [Accessed 14/12/2017 2017].

UGLOW, C. 1980. A study of the effects of thermal capacity on domestic heating energy requirements. *Building Services Engineering Research and Technology,* 1**,** 123-127.

UGLOW, C. 1981. The calculation of energy use in dwellings. *Building Services Engineering Research and Technology,* 2**,** 1-14.

UGLOW, C. 1982. Energy use in dwellings: An exercise to investigate the validity of a simple calculation method. *Building Services Engineering Research and Technology,* 3**,** 35-39.

USDOE. *EnergyPlus* [Online]. Available: https://energyplus.net/ [Accessed].

USDOE 2013. US Department of Energy Weather Data files. *In:* ENERGY, U. D. O. (ed.).

USDOE. 2018. *EnergyPlus* [Online]. Available: https://energyplus.net/ [Accessed].

VADODARIA, K., LOVEDAY, D. & HAINES, V. 2014. Measured winter and spring-time indoor temperatures in UK homes over the period 1969-2010: A review and synthesis. *Energy Policy,* 64**,** 252-262.

VOSS, K., GOETZBERGER, A., BOPP, G., HÄBERLE, A., HEINZEL, A. & LEHMBERG, H. 1996. The self-sufficient solar house in Freiburg—Results of 3 years of operation. *Solar Energy,* 58**,** 17-23.

VROM-INSPECTIE 2009. Gebruik en betrouwbaarheid energielabels bij woningen. Ministerie van VROM.

WADE, F., HITCHINGS, R. & SHIPWORTH, M. 2016. Understanding the missing middlemen of domestic heating: Installers as a community of professional practice in the United Kingdom. *Energy Research & Social Science,* 19**,** 39-47.

WADE, F., SHIPWORTH, M. & HITCHINGS, R. 2017. How installers select and explain domestic heating controls. *Building Research & Information,* 45**,** 371-383.

WAECHTER, S., SÜTTERLIN, B. & SIEGRIST, M. 2015. The misleading effect of energy efficiency information on perceived energy friendliness of electric goods. *Journal of Cleaner Production,* 93**,** 193-202.

WAUMAN, B., BREESCH, H. & SAELENS, D. 2013. Evaluation of the accuracy of the implementation of dynamic effects in the quasi steady-state calculation method for school buildings. *Energy and Buildings,* 65**,** 173-184.
WEBER, C., GEBHARDT, B. & FAHL, U. 2002. Market transformation for energy efficient technologies — success factors and empirical evidence for gas condensing boilers. *Energy,* 27**,** 287-315.
WETTER, M., NOUIDUI, T. S. & HAVES, P. 2016. *Building Control Virtual Test Bed BCVTB* [Online]. Lawrence Berkeley National Laboratory. Available: http://simulationresearch.lbl.gov/bcvtb/ [Accessed].
WIEL, S., EGAN, C. & DELTA CAVA, M. 2006. Energy efficiency standards and labels provide a solid foundation for economic growth, climate change mitigation, and regional trade. *Energy for Sustainable Development,* 10**,** 54-63.
WINGFIELD, J., JOHNSTON, D. & MILES-SHELTON, D. 2010. Whole House Heat Loss Test Method (Coheating). 2018.
WINSLOW, C. E. A. 1949. *Temperature and human life,* Princeton, N. J., Princeton, N. J. : Princeton University Press.
WOLFF, D., TEUBER, P., BUDDE, J. & JAGNOW 2004. Felduntersuchung:Betriebsverhalten von Heizungsanlagen mit Gas-Brennwertkesseln. Fachhochschule Braunschweig Wolfenbüttel.
YANG, R. & NEWMAN, M. W. 2013. Learning from a learning thermostat. 93.
ZCH 2014. Design vs as-built performance gap - end of term report (Zero Carbon Hub).
ZERWAS, K., ZENS, FREY 2008. Energieausweis nach DIN V 18599 und mittels Gebaudesimulation ein Projektbericht. *Bauphysik,* 30**,** 174-186.

9 Appendices

9.1 Appendix A: German rental contract example

Wohnraummietvertrag

Zwischen [redacted]
(Vor- und Zuname)

(Vor- und Zuname)
[redacted]
(Straße Nr., PLZ, Ort)
[redacted]
(Telefon) (Fax) (E-Mail) als Vermieter/in

und [redacted]
(Vor- und Zuname) (Geburtsdatum)
[redacted]
(Vor- und Zuname) (Geburtsdatum)
[redacted]
(Straße Nr., PLZ, Ort)
[redacted]
(Telefon) (Fax) (E-Mail) als Mieter/in

wird folgender Mietvertrag geschlossen:

§ 1 Mietsache

1. Vermietet werden im 1.OG Geschoss ~~links~~ – rechts des Hauses Haldenstr. 33

in 73730 Esslingen zu Wohnzwecken und alleiniger Nutzung:

3	Zimmer	1	Keller/Nr. 4	Sonstiges/Wohnungszubehör (z.B. Einbauküche)
1	Küche		Abstellraum/Nr.	~~Einbauküche mit elektr. Geräten (gemäß Über-~~
1	Bad/Dusche		Garten/Nr.	~~gabeprotokoll)~~
	separates WC	1	Stellplatz/Nr. 4 (außen)	~~Möblierung im Ankleide-~~ zimmer
	Balkon/Terrasse		Garage/Nr.	Spiegelschrank im Bad
				Garderobe im Flur

☒ Es handelt sich um eine Eigentumswohnung.

2. Beheizung

☐ Einzelofen ☐ Etagenheizung ☒ Zentralheizung

3. Gemeinschaftlich

☒ Waschküche ☐ Trockenraum ☐ Garten ☐ Sonstiges:

4. Ausgehändigte Schlüssel gemäß Übergabeprotokoll

___ Schließanlage ___ Wohnung ___ Briefkasten ___ Garage ___ Zugangskarte

___ Haustür ___ Zimmer ___ Keller ___ Handsender

Die Anfertigung von zusätzlichen Schlüsseln vom Haus und gemeinsam benutzten Räumen ist nur mit vorheriger Zustimmung des Vermieters gestattet. Schlüssel, die der Mieter sich zusätzlich beschafft hat, sind nach Beendigung der Mietzeit dem Vermieter herauszugeben.

 Seite 1 von 8

Hausordnung

1. Vorbemerkung
Der Vermieter ist berechtigt, die Hausordnung zur Aufrechterhaltung der Ruhe und Ordnung im Haus einseitig abzuändern, soweit dadurch keine zusätzlichen Verpflichtungen des Mieters entstehen.

2. Rücksichtnahme
Die Hausbewohner verpflichten sich zur gegenseitigen Rücksichtnahme, sowie zum sachgemäßen Umgang mit der Mietsache und den Gemeinschaftsflächen.

3. Ruhezeiten
In der Zeit von 13.00 - 15.00 Uhr sowie 22.00 - 6.00 Uhr ist Ruhe auf Zimmerlautstärke einzuhalten. Insbesondere ist zu diesen Zeiten zu vermeiden:
Starkes Türenschlagen; ruhestörende Haus- und Gartenarbeiten. An Sonn- und Feiertagen ist die Erledigung solcher ruhestörender Arbeiten ganztägig zu unterlassen.
Bei der Benutzung von Fernseh-, Radio- oder sonstigen elektronischen Geräten sowie Musikinstrumenten ist stets Zimmerlautstärke einzuhalten.

4. Reinigung
Die Zugänge zu den einzelnen Wohnungen, die Treppen, sowie die Treppenfenster einschließlich der Geländer sind von den jeweiligen Parteien (Mietern) stets sauber zu halten. Wohnen mehrere Parteien auf einem Stockwerk, so hat die Reinigung abwechselnd zu erfolgen.
Die Reinigung, Räumung und Bestreuung der gemeinschaftlich genutzten Treppen, Räume, Plätze, Einfahrten und Höfe, sowie der Straße und Gehwege wechselt von Woche zu Woche zwischen allen Hausbewohnern in fortlaufender Reihe. Die Reinigung der Straßen und Gehwege muss nach den jeweiligen Polizeivorschriften mindestens 1x wöchentlich, bei Bedarf täglich, vorgenommen werden. Insbesondere ist die ausreichende Beseitigung von Schnee und Eis sicherzustellen. Der Vermieter ist nicht verpflichtet, Reinigungsgeräte und Streumaterial zu stellen.
Kommt der Mieter seiner Reinigungspflicht nicht ordnungsgemäß nach, so ist der Vermieter berechtigt nach erfolgloser Mahnung die Reinigung, Räumung und Bestreuung auf Kosten des Mieters ausführen zu lassen.

5. Gemeinschaftseinrichtungen
Gemeinschaftseinrichtungen dürfen nur zu den dafür vorgesehenen Zwecken benutzt werden. Insbesondere ist das Rauchen in diesen Einrichtungen sowie im Treppenhaus und den Allgemeinfluren nicht erlaubt.
Das Einstellen von Krafträdern ist in den zur Alleinbenutzung gemieteten Haupt- und Nebenräumen nicht gestattet.
Hauseingang, Treppen, Flure, Keller und Gemeinschaftsräume sind von Gegenständen aller Art, mit Ausnahme von Kinderwägen, Gehilfen und Rollstühlen, die Fluchtwege nicht versperren und keine wesentlichen Hindernisse darstellen, freizuhalten.

6. Außentüren
Die Haustüre ist stets geschlossen zu halten, darf jedoch aus Gründen der Fluchtmöglichkeit auch während der Nachtruhe nicht abgeschlossen werden. Sämtliche Türschlüssel sind sorgfältig aufzubewahren und dürfen nur Familienmitgliedern oder Untermietern überlassen werden.

7. Lüften und Heizen
Der Mieter hat für ausreichende Lüftung und Heizung der Mietsache Sorge zu tragen. Zum Lüften sind die Fenster kurzzeitig ganz zu öffnen (Stoßlüften).

8. Abfallbeseitigung
Müll darf frühestens am Abend vor der Abholung auf den Gehweg gestellt werden.
Die Zwischenlagerung von Sperrmüll ist weder in den Gemeinschaftsräumen noch der Außenanlage gestattet.
Abfälle dürfen nicht ins WC geworfen werden.

9. Brennmaterial
Im Interesse des Feuerschutzes dürfen leichtentzündliche Gegenstände nicht in den Keller- und Bodenräumen sowie in der Garage gelagert werden.
Brennstoffe dürfen nur in den hierfür ausgewiesenen Räumen gelagert werden. Öfen und Herde dürfen nur mit dem jeweils geeigneten Brennstoff beheizt werden.

10. Waschen und Trocknen
Während des Waschens ist die Waschküchentür geschlossen zu halten. Die Wäsche ist auf dem vom Vermieter bestimmten Trockenplatz zu trocknen und darf nur solange aufgehängt werden, wie es der Trockenvorgang erfordert. Es ist darauf zu achten, dass der Wasch-/Trockenraum nach Benutzung ausreichend gelüftet und beheizt wird.

11. Kälteschutz
Der Mieter hat alle möglichen Maßnahmen zu ergreifen, um ein Einfrieren von Leitungen zu verhindern. Ab –5°C kann die Wasserleitung bei Einfriergefahr abgestellt werden. Befindet sich der Haupthahn in den Räumen des Mieters, so muss dieser den Zutritt bei Bedarf ermöglichen.

12. Grillen
Grillen innerhalb der Mietsache und auf dem Grundstück ist nur in Ausnahmefällen gestattet, sofern keine Belästigungen auftreten.

13. Allgemeinbeleuchtung
Fällt die Allgemeinbeleuchtung im Bereich Hauseingang und Treppenhaus aus, so muss jeder Mieter im Rahmen einer Notversorgung das Treppenhaus seines Stockwerks, der Mieter des Erdgeschosses auch den Hauseingang beleuchten.

14. Außenantennen, Blumenkästen, etc.
Das Anbringen von Außenantennen, Blumenkästen, Schildern und ähnlichen Vorrichtungen darf nur mit vorheriger Zustimmung des Vermieters in sachgemäßer Ausführung erfolgen. Außenantennen sind zu entfernen, wenn der Vermieter nachträglich eine Gemeinschaftsantenne anbringt.
Die Zustimmung kann vom Vermieter aus wichtigem Grund widerrufen werden.

15. Gartenpflege
Soweit der Mieter die Gartenpflege zu erledigen hat, ist der Vermieter nicht verpflichtet Arbeitsgeräte zu stellen.

2. Einrichtungen oder Veränderungen der Mietsache, die der Mieter ohne Zustimmung des Vermieters während der Mietzeit angebracht oder vorgenommen hat, hat der Mieter auf Verlangen des Vermieters sofort auf eigene Kosten zu beseitigen und den ursprünglichen Zustand wiederherzustellen.
   Bei genehmigten Veränderungen oder Einrichtungen muss der Mieter bei Beendigung des Mietverhältnisses diese auf eigene Kosten beseitigen und den ursprünglichen Zustand wiederherstellen, soweit nichts Abweichendes vereinbart ist.

3. Will der Mieter Einrichtungen, mit denen er die Mietsache versehen hat, bei Beendigung des Mietverhältnisses wegnehmen, hat er sie zunächst dem Vermieter zur Übernahme anzubieten. Wenn der Vermieter die Einrichtungen übernehmen will, hat er nach seiner Wahl entweder dem Mieter die Herstellungskosten abzüglich eines angemessenen Betrages für die Abnutzung zu erstatten oder in sonstiger Weise einen angemessenen Ausgleich zu leisten. Macht der Vermieter von diesem Recht keinen Gebrauch und nimmt der Mieter die Einrichtungen weg, so ist der Mieter zur Wiederherstellung des ursprünglichen Zustands verpflichtet.

4. Aufstellung und Betrieb von (Kamin-) Öfen oder Abluft-Wäschetrocknern bedürfen der vorherigen Zustimmung des Vermieters. Bei Aufstellung und Betrieb dieser Geräte hat der Mieter alle gesetzlichen und behördlichen Vorschriften und Auflagen zu beachten.

§ 9 Erhaltung der Mietsache

Die Kosten für auch **ohne Verschulden** des Mieters notwendige Reparaturen an solchen Gegenständen, welche dem häufigen und unmittelbaren Zugriff des Mieters ausgesetzt sind, z. B. Installationsgegenstände für Elektrizität, Wasser und Gas, Heiz- und Kocheinrichtungen, Fenster- und Türverschlüsse, Verschlussvorrichtungen für Fensterläden, Rollläden, Jalousien sowie Markisen (Kleinreparaturen) hat der Mieter zu tragen, soweit die Kosten für die einzelne Reparatur **125,00 €** und der dem Mieter dadurch entstehende jährliche Aufwand 6% der Jahresnettomiete innerhalb von zwölf Monaten nicht übersteigt.

§ 10 Zentrale Heizungs- und Warmwasserversorgung, Raumtemperatur

1. Die dem Tagesaufenthalt dienenden Räume werden während der Heizperiode (1. Oktober bis 30. April) in der Zeit von 6.00 - 23.00 Uhr mit einer Temperatur von mindestens 20°C beheizt.
   Für die sonstigen Räume genügt eine angemessene, der technischen Anlage entsprechende Erwärmung. Außerhalb der Heizperiode ist es Sache des Mieters, durch eigene Übergangsheizung für eine seinen Wünschen entsprechende Raumtemperatur zu sorgen. Soweit der Mieter die Heizung allein betreibt (Etagenheizung), ist er verpflichtet, die Heizung im üblichen Umfang ständig in Betrieb zu halten.

2. Eine Beheizung außerhalb der Heizperiode kann nur verlangt werden, wenn an mindestens drei aufeinanderfolgenden Tagen die Außentemperatur (gemessen 12.00 Uhr mittags) unter 12°C absinkt. Bei Störungen der Heizanlage, höherer Gewalt, behördlichen Anordnungen oder sonstiger Unmöglichkeit der Leistung (z. B. Brennstoffknappheit) ist der Vermieter zur Ersatzbeheizung nicht verpflichtet. Er hat etwaige Störungen schnellstmöglich beseitigen zu lassen.

3. Sofern die Mietsache nicht über Klimatechnik verfügt, kann der Mieter keine Maßnahmen zur Reduzierung der Innentemperatur verlangen.

4. Bei Auszug trägt der Mieter die Kosten der Zwischenablesung bis zu einem Betrag in Höhe von 70,00 €.

5. Der Vermieter ist berechtigt, die Wärmeversorgung auf einen Dritten zu dessen Bedingungen zu übertragen (Wärmecontracting). Der Mieter verpflichtet sich, die hierdurch zusätzlich anfallenden Kosten zu übernehmen, soweit die nach der Wärmelieferverordnung (WärmeLV) vorgegebenen Voraussetzungen vorliegen.

6. Der Vermieter kann nach Anlieferung von Brennstoffen vom Mieter die Zahlung eines Anteils an den Brennstoffkosten jeweils binnen zwei Wochen nach Rechnungslegung verlangen. Abrechnung über die übrigen Heizkosten erfolgt nach Ablauf der Heizzeiten.

§ 11 Personenmehrheiten

1. Mehrere Mieter haften für alle Verpflichtungen aus dem Mietverhältnis als Gesamtschuldner.

2. Die Erklärungen von einem oder an einen Mieter sind für die anderen rechtsverbindlich. Die Mieter gelten insoweit als gegenseitig bevollmächtigt, ausgenommen bei Kündigungen und Mietaufhebungsvereinbarungen.

3. Bei einer Mehrheit von Vermietern ist jeder berechtigt, Erklärungen mit Wirkung für die anderen abzugeben und entgegenzunehmen. Die Vermieter gelten insoweit als gegenseitig bevollmächtigt.

4. Tatsachen, die für einen Ehegatten oder Mitmieter eine Verlängerung oder Verkürzung des Mietverhältnisses herbeiführen oder für ihn einen Schadensersatz- oder ähnlichen Anspruch oder eine Schadensersatzpflicht begründen, haben für den anderen Ehegatten oder Mitmieter die gleiche Wirkung.

9.2 Appendix B: SAP Test case

SAP 2009 input data (new dwelling as built) Printed on 07 Jun 2012 at 12:39

Filename: EW-1a-detached.bsp (File saved: 29 Aug 2011 11:37)

1a-detached

Country:	England & Wales
Region:	East Pennines
Postcode:	
UPRN:	0000000000
RRN:	(not assigned)
Date of assessment:	26 August 2011
Date of certificate:	07 June 2012
Assessment type:	New dwelling as built
Transaction type:	New dwelling
Related party disclosure:	No related party

Property description

Dwelling type:	House	
Detachment:	Detached	
Year completed:	2011	
	Floor area	Storey height
Ground floor	50.00 m²	2.40 m
First floor	50.00 m²	2.60 m

Living area: 30.00 m² (fraction 0.300)

Front of dwelling faces: East

Opening types

Name	Source	Type	Glazing	Argon	Frame
Doors	SAP	Solid door			
Windows (1)	manu.	Window	Double		

Opening types (continued)

Name	Gap	Frame Factor	g-value	U-value	Description
Doors				3.00	
Windows (1)		0.70	0.72	1.20	Data from Manufacturer
ABC					

Openings

Name	Type-Name	Location	Orient.	Width	Height
1	Doors	Walls (1)	n/a	2.00	1.00
2	Windows (1)	Walls (1)	East	23.00	1.00

Overshading: Average

	Gross area	Openings	Net area	U-value	κ-value	Description
Doors			2.00	3.00		
Windows (1)			23.00	1.20		
Ground floor			50.00	0.20	80	
Walls (1)	150.00	25.00	125.00	0.18	60	
Roof (1)	50.00		50.00	0.13	9	
Internal wall (1)			200.00		75	
Internal floor level 1 from below			50.00		9	
Internal floor level 1 from above			50.00		18	

Thermal bridges: User-defined y-value
y = 0.080
Reference: Thermal bridging for 1a.doc

Thermal mass: Calculated from κ values

Pressure test: Yes (measured in this dwelling)
Ventilation: Natural ventilation (extract fans)
Number of chimneys: 0
Number of open flues: 0
Number of intermittent fans: 3
Number of passive stacks: 0
Number of sides sheltered: 2
q50 measured in this dwelling: 4.00

Main heating system: Boiler system with radiators or underfloor
Fuel: Mains gas
Manufacturer's data:
Brand/Model:
Combi - no store or keep-hot, room-sealed flue, fan-

assisted

SEDBUK(2005) 90.0%, condensing, modulating burner control

	Radiators
	Central heating pump in heated space
Main heating controls:	2106 Programmer, room thermostat and TRVs
	Boiler interlock: Yes
Secondary heating:	None
Space cooling system:	None
Water heating:	901 From main system
	No hot water cylinder
	Solar panel: No
Water use <= 125 litres/person/day	No
Electricity tariff:	Standard tariff
Conservatory:	No
Photovoltaics:	None
Terrain type:	Rural
Wind turbine:	No
Total fixed lighting outlets:	10
Low energy fixed lighting outlets:	3 (= 30% of total outlets)
EPC language	English

Results summary -- New dwelling as built -- Worksheet version 9.90 -- bsap2009 v 5.34q

Regulations: Approved Document L1A, 2010 Edition

SAP 2009 = C 80   EI 2009 = B 82   DER = 20.87   TER = 19.49   FEE = 55.1

Heat demand kWh: space 4088   water 2240

PCDF revision number:	322 (03 Apr 2012)
External Definitions revision number:	3.0 (01 Mar 2011)
Applicable recommendations:	Low energy lighting [E]
	Solar water heating [N]
	Solar photovoltaic (PV) panels [U]
	Wind turbine [V]

SAP 2009 WORKSHEET FOR NEW DWELLING AS BUILT (Version 9.90, March 2010)

CALCULATION OF FABRIC ENERGY EFFICIENCY

calculated by program bsap2009 version 5.34q, printed on 07 Jun 2012 at 12:39

Filename: EW-1a-detached.bsp (File saved: 29 Aug 2011 11:37)

1a-detached

1. Overall dwelling dimensions	Area (m^2)	Av. storey height (m)	Volume (m^3)	
Ground floor	50.0000	2.4000	120.0000	(1b) - (3b)
First floor	50.0000	2.6000	130.0000	(1c) - (3c)
Total floor area	100.0000			(4)
Dwelling volume (m^3)			250.0000	(5)

2. Ventilation rate

	main		sec.		other		total		m^3 per hour	ach	
Number of chimneys	0	+	0	+	0	=	0	× 40	0		(6a)
Number of open flues	0	+	0	+	0	=	0	× 20	0		(6b)
Number of intermittent fans							3	× 10	30		(7a)
Number of passive vents							0	× 10	0		(7b)
Number of flueless gas fires							0	× 40	0		(7c)
Infiltration due to chimneys, flues and fans										0.1200	(8)
Pressure test							Yes				
q50 measured in this dwelling							4.0000				

Infiltration rate	0.3200	(18)
Number of sides sheltered	2	(19)
Shelter factor	0.8500	(20)
Infiltration rate incorporating shelter factor	0.2720	(21)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Wind speed	5.4000	5.1000	5.1000	4.5000	4.1000	3.9000	3.7000	3.7000	4.2000	4.5000	4.8000	5.1000	(22)
Wind factor	1.3500	1.2750	1.2750	1.1250	1.0250	0.9750	0.9250	0.9250	1.0500	1.1250	1.2000	1.2750	(22a)
Adj infilt rate	0.3672	0.3468	0.3468	0.3060	0.2788	0.2652	0.2516	0.2516	0.2856	0.3060	0.3264	0.3468	(22b)
Natural ventilation													
Effective ach	0.5674	0.5601	0.5601	0.5468	0.5389	0.5352	0.5317	0.5317	0.5408	0.5468	0.5533	0.5601	(25)

3. Heat losses and heat loss parameter

Element	Gross area (m^2)	Openings (m^2)	Net area (m^2)	U-value (W/m^2K)	A × U (W/K)	kappa (kJ/m^2K)	A × kappa (kJ/K)	
Doors			2.0000	3.0000	6.0000			(26)
Windows (Uw = 1.20)			23.0000	1.1450	26.3359			(27)
Ground floor			50.0000	0.2000	10.0000	80.0000	4000.0000	(28a)
Walls	150.00	25.00	125.0000	0.1800	22.5000	60.0000	7500.0000	(29a)
Roof	50.00		50.0000	0.1300	6.5000	9.0000	450.0000	(30)
Total area of external elements			250.0000					(31)
Fabric heat loss					71.3359			(33)
Internal wall			200.0000			75.0000	15000.0000	(32c)
Internal floor level 1 from below			50.0000			9.0000	450.0000	(32e)
Internal floor level 1 from above			50.0000			18.0000	900.0000	(32d)
Heat capacity							28300.0000	(34)
Thermal mass parameter							283.0000	(35)

Thermal bridges (0.080 × total area)					20.0000			(36)					
Total fabric heat loss					91.3359			(37)					
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Vent loss	46.8120	46.2111	46.2111	45.1125	44.4563	44.1512	43.8612	43.8612	44.6147	45.1125	45.6446	46.2111	(38)
Heat transfer coeff	138.1479	137.5470	137.5470	136.4484	135.7922	135.4870	135.1971	135.1971	135.9505	136.4484	136.9805	137.5470	(39)
Heat transfer coeff (average)											136.5242		(39)
HLP	1.3815	1.3755	1.3755	1.3645	1.3579	1.3549	1.3520	1.3520	1.3595	1.3645	1.3698	1.3755	(40)
HLP (average)											1.3652		(40)

Days in month

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
	31	28	31	30	31	30	31	31	30	31	30	31	(41)

4. Water heating energy requirements

Assumed occupancy											2.7395		(42)
Average daily water use (litres/day)											104.4881		(43)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Daily water use	114.9370	110.7574	106.5779	102.3984	98.2189	94.0393	94.0393	98.2189	102.3984	106.5779	110.7574	114.9370	(44)
Energy content	170.8560	149.4317	154.2001	134.4354	128.9940	111.3120	103.1469	118.3626	119.7762	139.5877	152.3709	165.4649	(45)
Energy content (annual)											1647.9384		(45)
Distribution loss	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	(46)
Storage loss	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	(57)
Primary circuit loss (annual)											0.0000		(58)
Primary loss	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	(59)
Heat gains (kWh)	36.3069	31.7542	32.7675	28.5675	27.4112	23.6538	21.9187	25.1521	25.4525	29.6624	32.3788	35.1613	(65)

5. Internal gains

(in watts)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Metabolic	136.9763	136.9763	136.9763	136.9763	136.9763	136.9763	136.9763	136.9763	136.9763	136.9763	136.9763	136.9763	(66)
Lighting	22.8518	20.2968	16.5064	12.4964	9.3412	7.8863	8.5214	11.0764	14.8667	18.8768	22.0320	23.4869	(67)
Appliances	256.3278	258.9876	252.2848	238.0153	220.0027	203.0733	191.7634	189.1036	195.8064	210.0759	228.0885	245.0179	(68)
Cooking	36.6976	36.6976	36.6976	36.6976	36.6976	36.6976	36.6976	36.6976	36.6976	36.6976	36.6976	36.6976	(69)
Pumps, fans	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	(70)
Losses	-109.5810	-109.5810	-109.5810	-109.5810	-109.5810	-109.5810	-109.5810	-109.5810	-109.5810	-109.5810	-109.5810	-109.5810	(71)
Water heating	48.7996	47.2533	44.0424	39.6771	36.8430	32.8525	29.4607	33.8065	35.3506	39.8688	44.9706	47.2598	(72)
Total internal	392.0721	390.6306	376.9266	354.2818	330.2798	307.9050	293.8384	298.0794	310.1166	332.9143	359.1839	379.8575	(73)

6. Solar gains

(calculation for January)

Orientation		Area	Flux	g	FF	Shading	Gains (W)	
East	0.9 ×	23.0000	19.8726	0.72	0.7000	0.77	159.6414	(76)
						total:	159.6414	(83-1)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Solar gains	159.6414	309.4304	494.5694	734.3182	893.4562	932.2760	904.8795	787.5364	591.2779	376.8281	198.4757	131.6884	(83)
Total gains	551.7135	700.0610	871.4959	1088.6000	1223.7360	1240.1810	1198.7179	1085.6158	901.3946	709.7424	557.6597	511.5459	(84)

7. Mean internal temperature

	°C	
Living room temperature during heating periods Th 1	21.0000	(85)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
tau	56.9036	57.1522	57.1522	57.6124	57.8907	58.0211	58.1456	58.1456	57.8233	57.6124	57.3885	57.1522	
alpha	4.7936	4.8101	4.8101	4.8408	4.8594	4.8681	4.8764	4.8764	4.8549	4.8408	4.8259	4.8101	
external temp.	4.5000	5.0000	6.8000	8.7000	11.7000	14.6000	16.9000	16.9000	14.3000	10.8000	7.0000	4.9000	
util living area	0.9992	0.9972	0.9885	0.9530	0.8421	0.6572	0.4566	0.5010	0.8335	0.9808	0.9982	0.9993	(86)
MIT 1	19.5844	19.7680	20.1049	20.4736	20.8090	20.9572	20.9942	20.9914	20.8688	20.4286	19.8830	19.6034	(87)

Th 2	19.7807	19.7853	19.7853	19.7938	19.7988	19.8012	19.8034	19.8034	19.7976	19.7938	19.7897	19.7853	(88)
util rest of house	0.9988	0.9961	0.9835	0.9334	0.7822	0.5520	0.3265	0.3600	0.7435	0.9690	0.9973	0.9990	(89)
MIT 2	18.5029	18.6896	19.0237	19.3850	19.6816	19.7846	19.8025	19.8019	19.7341	19.3507	18.8083	18.5256	(90)
Living area fraction = 30.00 ÷ 100.00 =											0.3000		(91)
MIT	18.8274	19.0131	19.3480	19.7116	20.0198	20.1364	20.1600	20.1588	20.0746	19.6741	19.1307	18.8490	(92)
Temperature adjustment											0.0000		
adjusted MIT	18.8274	19.0131	19.3480	19.7116	20.0198	20.1364	20.1600	20.1588	20.0746	19.6741	19.1307	18.8490	(93)

8. <u>Space heating requirement</u>

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Utilisation	0.9984	0.9951	0.9811	0.9317	0.7946	0.5830	0.3659	0.4029	0.7673	0.9674	0.9966	0.9987	(94)
Useful gains W	550.8413	696.6365	855.0623	1014.2601	972.3744	723.0512	438.6158	437.3406	691.6722	686.5933	555.7488	510.8960	(95)
Ext temp.	4.5000	5.0000	6.8000	8.7000	11.7000	14.6000	16.9000	16.9000	14.3000	10.8000	7.0000	4.9000	(96)
Heat loss rate W	1979.2932	1927.4649	1725.9433	1502.5129	1129.7685	750.1051	440.7409	440.5785	785.0532	1210.8502	1661.6744	1918.6384	(97)
Space heating kWh	1062.7682	827.1167	647.9354	351.5421	117.1012	–	–	–	–	390.0472	796.2664	1047.3603	(98)
Space heating (October to May)											5240.1376		(98)
Space heating per m²											52.4014		(99)

8c. <u>Space cooling requirement</u>

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Ext temp.	–	–	–	–	–	14.6000	16.9000	16.9000	–	–	–	–	
Heat loss rate W	–	–	–	–	–	1273.5781	959.8995	959.8995	–	–	–	–	(100)
Utilisation	–	–	–	–	–	0.9006	0.9563	0.9402	–	–	–	–	(101)
Useful loss W	–	–	–	–	–	1147.0376	917.9945	902.4988	–	–	–	–	(102)
Gains W	–	–	–	–	–	1554.3031	1503.5968	1373.2060	–	–	–	–	(103)
Space cooling kWh	–	–	–	–	–	293.2312	435.6880	350.2062	–	–	–	–	(104)
Space heating kWh	–	–	–	–	–	8.2706	0.5857	0.8754	–	–	–	–	(98)

month included	–	–	–	–	–	1	1	1	–	–	–	–	
Space cooling kWh	–	–	–	–	–	293.2312	435.6880	350.2062	–	–	–	–	(104)
Cooled fraction = 100.00 ÷ 100.00 =												1.0000	(105)
Intermittency factor	–	–	–	–	–	0.2500	0.2500	0.2500	–	–	–	–	(106)
Space cooling kWh	–	–	–	–	–	73.3078	108.9220	87.5515	–	–	–	–	(107)
Space cooling (June to August)												269.7813	(107)
Space cooling per m²												2.6978	(108)

8f. Fabric Energy Efficiency (kWh/m²) 52.4014 + 2.6978 = 55.0992

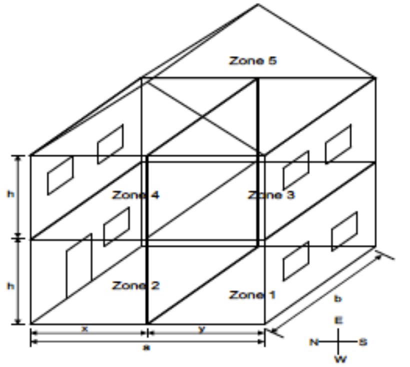
55.1 (109)

9.3 Appendix C: BTSL SAP Building Input

Building Description	1.00	Single family house, 2 storeys		**Zone Types**	**Custom Internal Temp in °C**	**Custom Infiltration Rate in 1/h**
Label/Location	SAP_EFH2		UK	**Custom Zone Type Mode:**		ON
Date/Author	18/03/2015		TT WB/PJ-FCS1 Bennett	Living Room	21	0.5647
Window Type	2-WSV,Argon,Gr.0-SAP			Bedroom	18	0.5647
WINID/U-Value Frame		2005	4	Office	21	0.5647
1.00	SverweisSpalten	9	8	Kitchen/Bathroom	19	0.5647
T_{flow}/T_{return} in °C		80	60	VRheated (Staircase/Lobby)	18	0.5647
Pipe Insulation	old			VRunheated (Attic/Cellar)	15	0.5647
				Design/Mean T Ext in °C	-2	8
Zone 1	**Geometric Specifications Zone 1**			**Heat Load Calculation Zone 1**		
Zone Type/Zone Description	Living Room		Living/Dining Room	**θ_e in °C**	**$\rho \cdot c_p$ in Wh/(m³K)**	**HL by Transmission Z1 in W**
Base Infiltration Rate in 1/h		0.56		-2	0.34	566.168
Air Volume in m³		73.49		**$\theta_{int,1}$ in °C**	**n_{min} in 1/h**	**HL by Ventilation Z1 in W**
Floor Area in m²		30.00		21	0.5647	320.611
Capacity in kJ/K		110.24		**$(\theta_{int,1}-\theta_e)$ in K**		**Total Heat Load Z1 in W**
1/Floorheating Area in 1/m²		0.033		23		886.779
External Walls	**Label**	**Area**	**Orientation**	**Rsi + Rse in m²K/W**	**U-Value in W/(m²K)**	**HL by Transmission in W**
External Wall East	SAP_ExtWall1	12.43	EXTERNAL: ORIENTATION =EAST : FSKY=0.5	0.17	0.19	83.967
External Wall South	SAP_ExtWall1	12.60	EXTERNAL: ORIENTATION =SOUTH : FSKY=0.5	0.17	0.19	85.109
External Wall West	SAP_ExtWall1	12.43	EXTERNAL: ORIENTATION =WEST : FSKY=0.5	0.17	0.19	83.967
External Wall Floor to Ground	SAPGd1Z@Zone	30.00	BOUNDARY = INPUT 1*TGround+0 : COUPL=0.0	0.17	0.13	62.734
External Wall	DUMMY	0.01	BOUNDARY=IDENTICAL : COUPL=0.000	0.26	2.08	0.050
Internal Walls	**Label**	**Area**	**Orientation**	**Rsi + Rse in m²K/W**	**U-Value in W/(m²K)**	**HL by Transmission in W**
To Zone 2	SAPInt3	17.72	FRONT	0.26	1.72	
To Zone 3	SAPFr1Z@Zone	30.00	BACK	0.34	0.28	
To Zone 4	DUMMY	0.01	BACK	0.26	2.08	
To Zone 5	DUMMY	0.01	BACK	0.26	2.08	0.402
Windows	**Label**	**Area**	**Orientation**		**U-Value in W/(m²K)**	**HL by Transmission in W**
Window	WIN	8.36	EAST		1.2	249.940
Zone 2	**Geometric Specifications Zone 2**			**Heat Load Calculation Zone 2**		
Zone Type/Zone Description	Kitchen/Bathroom		Kitchen/Bathroom/Lobby	**θ_e in °C**	**$\rho \cdot c_p$ in Wh/(m³K)**	**HL by Transmission Z2 in W**
Base Infiltration Rate in 1/h		0.56		-2	0.34	404.465
Air Volume in m³		48.50		**$\theta_{int,1}$ in °C**	**n_{min} in 1/h**	**HL by Ventilation Z2 in W**
Floor Area in m²		20.00		19	0.5647	193.168
Capacity in kJ/K		72.74		**$(\theta_{int,1}-\theta_e)$ in K**		**Total Heat Load Z2 in W**
1/Floorheating Area in 1/m²		0.050		21		597.633
External Walls	**Label**	**Area**	**Orientation**	**Rsi + Rse in m²K/W**	**U-Value in W/(m²K)**	**HL by Transmission in W**
External Wall North	SAP_ExtWall1	14.74	EXTERNAL: ORIENTATION =NORTH : FSKY=0.5	0.17	0.19	90.900
External Wall East	SAP_ExtWall1	8.53	EXTERNAL: ORIENTATION =EAST : FSKY=0.5	0.17	0.19	52.585
External Wall West	SAP_ExtWall1	8.53	EXTERNAL: ORIENTATION =WEST : FSKY=0.5	0.17	0.19	52.585
External Wall Floor to Ground	SAPGd1Z@Zone	20.00	BOUNDARY = INPUT 1*TGround+0 : COUPL=0.0	0.17361	0.13	38.188
External Wall 5	DUMMY	0.01	BOUNDARY=IDENTICAL : COUPL=0.000	0.26	2.08	0.046
Internal Walls	**Label**	**Area**	**Orientation**	**Rsi + Rse in m²K/W**	**U-Value in W/(m²K)**	**HL by Transmission in W**
To Zone 1	SAPInt3	17.72	BACK	0.26	1.72	
To Zone 3	DUMMY	0.01	BACK	0.26	2.08	
To Zone 4	SAPFr1Z@Zone	20.00	BACK	0.34	0.28	
To Zone 5	DUMMY	0.01	BACK	0.26	2.08	0.367
Windows	**Label**	**Area**	**Orientation**		**U-Value in W/(m²K)**	**HL by Transmission in W**
Window	WIN	6.22	EAST		1.2	169.795
Zone 3	**Geometric Specifications Zone 3**			**Heat Load Calculation Zone 3**		
Zone Type/Zone Description	Office		Children's Room	**θ_e in °C**	**$\rho \cdot c_p$ in Wh/(m³K)**	**HL by Transmission Z3 in W**

Base Infiltration Rate in 1/h		0.56		-2	0.34	606.800
Air Volume in m³		73.49		$\theta_{int,1}$ in °C	n_{min} in 1/h	HL by Ventilation Z3 in W
Floor Area in m²		30.00		21	0.5647	320.611
Capacity in kJ/K		110.24		$(\theta_{int,1}-\theta_e)$ in K		Total Heat Load Z3 in W
1/Floorheating Area in 1/m²		0.033		23		927.410
External Walls	**Label**	**Area**	**Orientation**	**Rsi + Rse in m²K/W**	**U-Value in W/(m²K)**	**HL by Transmission in W**
External Wall South	SAP_ExtWall1	15.50	EXTERNAL: ORIENTATION =SOUTH : FSKY=0.5	0.17	0.19	104.672
External Wall East	SAP_ExtWall1	11.67	EXTERNAL: ORIENTATION =EAST : FSKY=0.5	0.17	0.19	78.829
External Wall West	SAP_ExtWall1	11.67	EXTERNAL: ORIENTATION =WEST : FSKY=0.5	0.17	0.19	78.829
External Wall 4	DUMMY	0.01	BOUNDARY=IDENTICAL : COUPL=0.000	0.26	2.08	0.050
External Wall 5	DUMMY	0.01	BOUNDARY=IDENTICAL : COUPL=0.000	0.26	2.08	0.050
Internal Walls	**Label**	**Area**	**Orientation**	**Rsi + Rse in m²K/W**	**U-Value in W/(m²K)**	**HL by Transmission in W**
To Zone 1	SAPFr1Z@Zone	30.00	FRONT	0.34	0.28	
To Zone 2	DUMMY	0.01	FRONT	0.26	2.08	
To Zone 4	SAPInt3	17.72	FRONT	0.26	1.72	
To Zone 5	SAPCg1Z@Zone	30.00	BACK	0.20	0.30	219.399
Windows	**Label**	**Area**	**Orientation**		**U-Value in W/(m²K)**	**HL by Transmission in W**
Window	WIN	4.18	EAST		1.2	124.970
Zone 4	**Geometric Specifications Zone 4**			**Heat Load Calculation Zone 4**		
Zone Type/Zone Description	Bedroom		Bedroom	θ_e in °C	$\rho \cdot c_p$ in Wh/(m³K)	HL by Transmission Z4 in W
Base Infiltration Rate in 1/h		0.56		-2	0.34	421.004
Air Volume in m³		48.50		$\theta_{int,1}$ in °C	n_{min} in 1/h	HL by Ventilation Z4 in W
Floor Area in m²		20.00		18	0.5647	183.969
Capacity in kJ/K		72.74		$(\theta_{int,1}-\theta_e)$ in K		Total Heat Load Z4 in W
1/Floorheating Area in 1/m²		0.050		20		604.974
External Walls	**Label**	**Area**	**Orientation**	**Rsi + Rse in m²K/W**	**U-Value in W/(m²K)**	**HL by Transmission in W**
External Wall North	SAP_ExtWall1	15.50	EXTERNAL: ORIENTATION =NORTH : FSKY=0.5	0.17	0.19	91.019
External Wall East	SAP_ExtWall1	8.01	EXTERNAL: ORIENTATION =EAST : FSKY=0.5	0.17	0.19	47.016
External Wall West	SAP_ExtWall1	8.01	EXTERNAL: ORIENTATION =WEST : FSKY=0.5	0.17	0.19	47.016
External Wall 4	DUMMY	0.01	BOUNDARY=IDENTICAL : COUPL=0.000	0.26	2.08	0.044
External Wall 5	DUMMY	0.01	BOUNDARY=IDENTICAL : COUPL=0.000	0.26	2.08	0.044
Internal Walls	**Label**	**Area**	**Orientation**	**Rsi + Rse in m²K/W**	**U-Value in W/(m²K)**	**HL by Transmission in W**
To Zone 1	DUMMY	0.01	FRONT	0.26	2.08	
To Zone 2	SAPFr1Z@Zone	20.00	FRONT	0.34	0.28	
To Zone 3	SAPInt3	17.72	BACK	0.26	1.72	
To Zone 5	SAPCg1Z@Zone	20.00	BACK	0.2	0.30	127.195
Windows	**Label**	**Area**	**Orientation**		**U-Value in W/(m²K)**	**HL by Transmission in W**
Window	WIN	4.18	EAST		1.2	108.669
Zone 5	**Geometric Specifications Zone 5**			**Heat Load Calculation Building 'SAP_EFH2'**		
Zone Type/Zone Description	VRunheated (Attic/Cellar)		Attic		HL by Transmission Building 'SAP_EFH2' in kW	
Base Infiltration Rate in 1/h		0.56			1.998	
Air Volume in m³		1.54			HL by Ventilation Building 'SAP_EFH2' in kW	
Floor Area in m²		50.00			1.018	
Capacity in kJ/K		2.31			Total Heat Load Building 'SAP_EFH2' in kW	
1/Floorheating Area in 1/m²		0.020			3.017	
External Walls	**Label**	**Area**	**Orientation**	**R_{si} + R_{se} in m²K/W**	**U-Value in W/(m²K)**	
External Wall North	RFTW44	25.00	EXTERNAL: ORIENTATION =NORTH45 : FSKY=0	0.17	1.97	
External Wall South	RFTW44	25.00	EXTERNAL: ORIENTATION =SOUTH45 : FSKY=0	0.17	1.97	
External Wall East	SAP_ExtWall1	0.58	EXTERNAL: ORIENTATION =EAST : FSKY=0.5	0.17	0.19	
External Wall West	SAP_ExtWall1	0.58	EXTERNAL: ORIENTATION =WEST : FSKY=0.5	0.17	0.19	
External Wall 5	DUMMY	0.01	BOUNDARY=IDENTICAL : COUPL=0.000	0.26	2.08	
Internal Walls	**Label**	**Area**	**Orientation**			

To Zone 1	DUMMY	0.01	FRONT
To Zone 2	DUMMY	0.01	FRONT
To Zone 3	SAPCg1Z@Zone	30.00	FRONT
To Zone 4	SAPCg1Z@Zone	20.00	FRONT
Windows	**Label**	**Area**	**Orientation**
Window	DUMMYWIN	0.01	SOUTH
113			
Building Parameters	**Value**	**ExtWall Sverweis Spalten**	
Living Area: A_{living} in m²	100	R_{si} in m²K/W	19
Width/Length Ratio: a/b	1.00	R_{se} in m²K/W	20
Clear Height: h in m	2.5	ΣR_{layer} in m²K/W	21
w/z Ratio:		U-Value in W/(m²K)	22
x/y Ratio:	0.67	Type of Transfer	23
y/z Ratio:		Link	24
Roof Pitch: α_{RFT} in °	1	LinkThickness in m	25
Window Type	2-WSV,Argon,Gr.0-S.	Thickness in m	26
Window Ratio: c_{win}	0.14	SAP k value column	36
Room Door	existing (4cm wood)		
Pipe Insulation	old		
T_{flow} in °C	80		
T_{return} in °C	60		
Building Elements	**Label**	**Area in m²**	**U-Value in W/(m²K)**
Door	existing (4cm wood)	1.50	1.7613
Exterior Wall	SAP_ExtWall1	139.63	0.1936
Interior Load-bearing Wall	SAPInt3	35.36	1.7179
Ground Floor	SAPGd1Z@Zone	50.00	0.1273
Ceiling between storeys	SAPFr1Z@Zone	50.00	0.2817
Ceiling to Attic	SAPCg1Z@Zone	50.00	0.2975
Rooftop	RFTW44	50.01	1.9667
140			
Base Infiltration Rate in 1/h	**Value**	**Area in m²**	
Zone 1 (Living Room)	0.5647	30.00	
Zone 2 (Kitchen/Bathroom/Hallway)	0.5647	20.00	
Zone 3 (Children's Room)	0.5647	30.00	
Zone 4 (Bedroom)	0.5647	20.00	
Zone 5 (Attic)	0.5647	50.00	
Resulting measures:			
a in m	7.071067812		
b in m	7.071067812		
x in m	2.828531143		
y in m	4.242536669		
Volume V in m³	254.65		
Area Exterior Walls in m²	139.6273966		
Area Windows in m²	22.93797376		
Height of Attic	0.061712974		
Building Elements	**U-Value in W/(m²K)**	**Area in m²**	
Exterior Wall	0.19	139.63	
Ground Floor	0.13	50.00	
Ceiling to Attic	0.30	50.00	
HL-relevant Walls	0.20	239.63	



9.4 Appendix D: BTSL SAP User Block Mask code

```
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Date:   10.05.2016
% Author: TT/ENT Bennett

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% History:
%   10.05.2016 TT/ENT Bennett file created
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%============================================================================
% auto parameterization of mask
%============================================================================
%% Get mask parameter values and settings, change mask visibilities
% building_param = BTSL_Param(gcb,'ManAuto_Building');                  %sh
ould the block use user input or try to derive from house block
reduced_gain = BTSL_Param(gcb,'flag_reduced_gain');                     %is
 reduced gain option active?
%light_gain = BTSL_Param(gcb,'flag_light_gain');                        %is
 light gain option active? i.e. do you want solar gain to be calculated her
e (then solar gain needs to be set to zero in the weather file)
control_type = BTSL_Param(gcb,'control_type');                          % h
eating system control type, controller and TRVS,  from drop down list (from
 Table 4e in SAP)
DHW_type= BTSL_Param(gcb,'DHW_type');                                   %ty
pe of DHW system, this influences the losses
%light_LE=round(str2double(BTSL_Param(gcb,'light_LE'))/100,2);           %f
raction of low energy light fittings rounded to nearest 0,01
light_LE=str2double(BTSL_Param(gcb,'light_LE'))/100;
glazing_type=BTSL_Param(gcb,'glazing_type');
HLP=str2double(BTSL_Param(gcb,'HLP'));                                  %He
at Loss Parameter
window_area=str2double(BTSL_Param(gcb,'window_area'));                  %Aw
 window area in m2
frame_type=BTSL_Param(gcb,'frame_type');
infiltration_base=str2double(BTSL_Param(gcb,'infiltration_base'));      % a
ir permeability from presumed test value, plus the chimneys, excluding shel
ter and wind factors!
shelter_sides=str2double(BTSL_Param(gcb,'shelter_sides'));              % n
o of sides of building which are protected from wind and therefore have no
influnce on air change
shading=BTSL_Param(gcb,'shading');                                      % d
escription of roof and overhang shading in form of 4 levels,  light to heav
y
SAP_DIN=BTSL_Param(gcb,'SAP_DIN');                                      % u
ser input to determine of user should reflect SAP or DIN standard,  main di
fference in heating schedule and setpoint



%% Constants and common parameters
months={'Jan','Feb','Mar','Apr','May','Jun','Jul','Aug','Sep','Oct','Nov','
Dec'};
month_days=[31,28,31,30,31,30,31,31,30,31,30,31];
month_cumulative_secs=[0,2678400,2678400,...
    5101200,5101200,...
    7776000,7776000,...
```

```
    10368000,10368000,...
    13046400,13046400,...
    15638400,15638400,...
    18316800,18316800,...
    20995200,20995200,...
    23587200,23587200,...
    26265600,26265600,...
    28857600,28857600,...
    31536000,31536000];
% e.g. Jan begin =0 secs, end=2678400, feb begin=2678400 end=5097600
% etc....

%% OCCUPANCY
% Calculates the number of Occupants (N) as function of the Total Floor Are
a(TFA)
% N is not a round number
% N is defined as 1 if TFA is less than 13,9m2
% Reference Table 1b from SAP standard

Z1_FA=evalin('base','BuiStruct.Zone{1,1}.FloorArea'); %Zone 1 Floor Area
Z2_FA=evalin('base','BuiStruct.Zone{1,2}.FloorArea');
Z3_FA=evalin('base','BuiStruct.Zone{1,3}.FloorArea');
Z4_FA=evalin('base','BuiStruct.Zone{1,4}.FloorArea');
TFA=Z1_FA+Z2_FA+Z3_FA+Z4_FA;

if TFA<=13.9;
    Occupancy_Total=1;
else
    Occupancy_Total= 1 + 1.76*(1-exp(-0.000349*(TFA-13.9)^2))+0.0013*(TFA-
13.9);
end

Occupancy_Z1= Occupancy_Total*(Z1_FA/TFA); % Zone 1 Occupancy
Occupancy_Z2= Occupancy_Total*(Z2_FA/TFA); % Zone 2 Occupancy
Occupancy_Z3= Occupancy_Total*(Z3_FA/TFA); % Zone 3 Occupancy
Occupancy_Z4= Occupancy_Total*(Z4_FA/TFA); % Zone 4 Occupancy

Occupancy_Ratio_Z1=Occupancy_Z1/Occupancy_Total;
Occupancy_Ratio_Z2=Occupancy_Z2/Occupancy_Total;
Occupancy_Ratio_Z3=Occupancy_Z3/Occupancy_Total;
Occupancy_Ratio_Z4=Occupancy_Z4/Occupancy_Total;

%SAPSAPUserProfile.Occupancy.time=[0,31536000]; % Timebase for occupancy,
but since it is constant over day and night and over the year thenonly star
t and finish needed
SAPUserProfile.Occupancy.Total=Occupancy_Total;
SAPUserProfile.Occupancy.Z1=Occupancy_Z1;
SAPUserProfile.Occupancy.Z2=Occupancy_Z2;
SAPUserProfile.Occupancy.Z3=Occupancy_Z3;
SAPUserProfile.Occupancy.Z4=Occupancy_Z4;
SAPUserProfile.Occupancy.Z5=0;

%% Setpoint Temperatures and Controls

% Determination of Zone setpoint temperatures, SAP and DIN

switch SAP_DIN
    case {'SAP'}
    % SAP based on Control Type Ref
    % Table 4e and Table 4c from SAP standard
```

```
    z1_setpoint=21;    %default starting point for main control zone setpoi
nt temperature
    z234_setpoint=21;  %default starting point for main control zone setpoi
nt temperature,  although it is always reduced
    case {'DIN'}
        % DIN V 18599-10 recommended minimum internal temperature and
        % setback delta T
    z1_setpoint=21;    %default starting point for main control zone setpoi
nt temperature
    z234_setpoint=21;  %default starting point for main control zone setpoi
nt temperature,  although it is always reduced
    setback_T=z1_setpoint-5;
end
 switch SAP_DIN
    case {'SAP'}
% SAP bimodal heating schedule
% setpoint weekly time profile in seconds, 0700-0900 1600-2300 weekdays and
% 0700-2300 weekends
weekprofile_secs=[0,25200,25200,32400,32400,57600,57600,82800,82800,86400,8
6400,...
    111600,111600,118800,118800,144000,144000,169200,169200,172800,172800,.
..
    198000,198000,205200,205200,230400,230400,255600,255600,259200,259200,.
..
    284400,284400,291600,291600,316800,316800,342000,342000,345600,345600,.
..
    370800,370800,378000,378000,403200,403200,428400,428400,432000,432000,.
..
    457200,457200,514800,514800,518400,...
    543600,543600,601200,601200,604800]';
    case {'DIN'}
% DIN V 18599-10 standard heating/setback schedule
% setpoint weekly time profile in seconds, 0600-2300 weekdays and weekends
% nighttime setback temperature
weekprofile_secs=[0,21600,21600,82800,82800,86400,86400,...
    108000,108000,169200,169200,172800,172800,...
    194400,194400,255600,255600,259200,259200,...
    280800,280800,342000,342000,345600,345600,...
    367200,367200,428400,428400,432000,432000,...
    453600,453600,514800,514800,518400,...
    540000,540000,601200,601200,604800]';
 end

SAPUserProfile.time=[0];


for i=1:52
    SAPUserProfile.time=vertcat(SAPUserProfile.time,weekprofile_secs+((i-
1)*weekprofile_secs(end)));
end


if strfind(control_type,'TRV')>0
    Flag_TRV=1;                     %TRV use derived from control input fro
m user
else
    Flag_TRV=0;
end
```

```
% both SAP & DIN only: Determine which control type has been chosen, 1,2 or
 3 make first adjustment to setpoint temp
switch control_type
    case {'No time or thermostatic control of room temperature',...
            'Programmer, no room thermostat','Room thermostat only',...
            'Programmer and room thermostat'}
        control_group=1;
        if strfind(lower(control_type),'no')
            z1_setpoint=z1_setpoint+0.6;
        else

        end
    case {'Programmer and at least two room thermostats','Programmer, room
thermostat and TRVs',...
            'TRVs and bypass','Programmer, TRVs and bypass','Programmer, TR
Vs and flow switch',...
            'Programmer, TRVs and boiler energy manager'}
        control_group=2;
    case {'Time and temperature zone control'}
        control_group=3;
end

%Setpoint adjustment according to Table 9 from SAP Specification
if HLP>6 % limitation for HLP
    HLP=6;
else

end

switch control_group
    case 1
        z234_setpoint=21-0.5*HLP;
    case {2,3}
        z234_setpoint=21-HLP+0.085*HLP;
end

% Bring together time and temperature profiles into one variable

if strcmp(SAP_DIN,'DIN')

SAPUserProfile.z1_setpoint=[0];
zone1_weekprofile=[setback_T,setback_T,z1_setpoint,z1_setpoint,setback_T,se
tback_T,setback_T,...
    setback_T,z1_setpoint,z1_setpoint,setback_T,setback_T,setback_T,...
    setback_T,z1_setpoint,z1_setpoint,setback_T,setback_T,setback_T,...
    setback_T,z1_setpoint,z1_setpoint,setback_T,setback_T,setback_T,...
    setback_T,z1_setpoint,z1_setpoint,setback_T,setback_T,setback_T,...
    setback_T,z1_setpoint,z1_setpoint,setback_T,setback_T,...
    setback_T,z1_setpoint,z1_setpoint,setback_T,setback_T]';
                              %needs to be column vector

SAPUserProfile.z234_setpoint=[0];
zone234_weekprofile=[setback_T,setback_T,z234_setpoint,z234_setpoint,setbac
k_T,setback_T,setback_T,...
    setback_T,z234_setpoint,z234_setpoint,setback_T,setback_T,setback_T,...
    setback_T,z234_setpoint,z234_setpoint,setback_T,setback_T,setback_T,...
    setback_T,z234_setpoint,z234_setpoint,setback_T,setback_T,setback_T,...
    setback_T,z234_setpoint,z234_setpoint,setback_T,setback_T,setback_T,...
    setback_T,z234_setpoint,z234_setpoint,setback_T,setback_T,...
    setback_T,z234_setpoint,z234_setpoint,setback_T,setback_T]';
```

```
elseif strcmp(SAP_DIN,'SAP')
    % Week SetPoint profiles for SAP profile

SAPUserProfile.z1_setpoint=[0];
zone1_weekprofile=[0,0,z1_setpoint,z1_setpoint,0,0,z1_setpoint,z1_setpoint,
0,0,0,...
    0,z1_setpoint,z1_setpoint,0,0,z1_setpoint,z1_setpoint,0,0,0,...
    0,z1_setpoint,z1_setpoint,0,0,z1_setpoint,z1_setpoint,0,0,0,...
    0,z1_setpoint,z1_setpoint,0,0,z1_setpoint,z1_setpoint,0,0,0,...
    0,z1_setpoint,z1_setpoint,0,0,z1_setpoint,z1_setpoint,0,0,0,...
    0,z1_setpoint,z1_setpoint,0,0,...
    0,z1_setpoint,z1_setpoint,0,0]';
   %needs to be column vector

SAPUserProfile.z234_setpoint=[0];
zone234_weekprofile=[0,0,z234_setpoint,z234_setpoint,0,0,z234_setpoint,z234
_setpoint,0,0,0,...
    0,z234_setpoint,z234_setpoint,0,0,z234_setpoint,z234_setpoint,0,0,0,...
    0,z234_setpoint,z234_setpoint,0,0,z234_setpoint,z234_setpoint,0,0,0,...
    0,z234_setpoint,z234_setpoint,0,0,z234_setpoint,z234_setpoint,0,0,0,...
    0,z234_setpoint,z234_setpoint,0,0,z234_setpoint,z234_setpoint,0,0,0,...
    0,z234_setpoint,z234_setpoint,0,0,...
    0,z234_setpoint,z234_setpoint,0,0]';
end
% Expland to year profile, i.e. 52 Weeks

for i=1:52
    SAPUserProfile.z1_setpoint=vertcat(SAPUserProfile.z1_setpoint,zone1_wee
kprofile);
    SAPUserProfile.z234_setpoint=vertcat(SAPUserProfile.z234_setpoint,zone2
34_weekprofile);
end


%% Ventilation and Air change rates

shelter_factor=1-
(0.075*shelter_sides);                          % conversion of no. sheltere
d sides of bulding into air change fudge factor
infiltration_shelter=infiltration_base*shelter_factor;
wind_speed=[5.4,5.1,5.1,4.5,4.1,3.9,3.7,3.7,4.2,4.5,4.8,5.1];    % Reference
 22 in SAP
wind_factor=wind_speed./4;                                       % Reference
 22a in SAP worksheet
infiltration_adjusted=infiltration_shelter*wind_factor;

% for simplest case with natural ventilation
for i=1:12
    if infiltration_adjusted(i) >=1
        effective_ach(i)=infiltration_adjusted(i);
    else
        effective_ach(i)=0.5+((infiltration_adjusted(i)^2).*0.5);
    end
end


%% GAINS


%% Metabolic Gains
switch reduced_gain
```

```
    case 'off'
    for i=1:25

        SAPUserProfile.metabolic_gain.time(i)=month_cumulative_secs(i);
        SAPUserProfile.metabolic_gain.total(i)=60*Occupancy_Total;
        SAPUserProfile.metabolic_gain.Z1value(i)=60*Occupancy_Z1;% metaboli
c gain from people,  assuming 60W per person
        SAPUserProfile.metabolic_gain.Z2value(i)=60*Occupancy_Z2;
        SAPUserProfile.metabolic_gain.Z3value(i)=60*Occupancy_Z3;
        SAPUserProfile.metabolic_gain.Z4value(i)=60*Occupancy_Z4;
        SAPUserProfile.metabolic_gain.Z5value(i)=0;
    end
    case 'on'
    for i=1:25
        SAPUserProfile.metabolic_gain.time(i)=month_cumulative_secs(i);
        SAPUserProfile.metabolic_gain.total(i)=50*Occupancy_Total;
        SAPUserProfile.metabolic_gain.Z1value(i)=50*Occupancy_Z1;% metaboli
c gain from people,  assuming 50W per person
        SAPUserProfile.metabolic_gain.Z2value(i)=50*Occupancy_Z2;
        SAPUserProfile.metabolic_gain.Z3value(i)=50*Occupancy_Z3;
        SAPUserProfile.metabolic_gain.Z4value(i)=50*Occupancy_Z4;
        SAPUserProfile.metabolic_gain.Z5value(i)=0;
    end
end
if isrow(SAPUserProfile.metabolic_gain.time)==1 % convert from row to colum
n vector
    SAPUserProfile.metabolic_gain.time=SAPUserProfile.metabolic_gain.time';
    SAPUserProfile.metabolic_gain.total=SAPUserProfile.metabolic_gain.total
';
    SAPUserProfile.metabolic_gain.Z1value=SAPUserProfile.metabolic_gain.Z1v
alue';
    SAPUserProfile.metabolic_gain.Z2value=SAPUserProfile.metabolic_gain.Z2v
alue';
    SAPUserProfile.metabolic_gain.Z3value=SAPUserProfile.metabolic_gain.Z3v
alue';
    SAPUserProfile.metabolic_gain.Z4value=SAPUserProfile.metabolic_gain.Z4v
alue';
    SAPUserProfile.metabolic_gain.Z5value=SAPUserProfile.metabolic_gain.Z5v
alue';
end




%% Cooking Gains
switch reduced_gain
    case 'off'
    for i=1:25
        SAPUserProfile.cooking_gain.time(i)=month_cumulative_secs(i);
        SAPUserProfile.cooking_gain.total(i)=7*Occupancy_Total+35;
        SAPUserProfile.cooking_gain.Z1value(i)=SAPUserProfile.cooking_gain.
total(i)*Occupancy_Ratio_Z1;
        SAPUserProfile.cooking_gain.Z2value(i)=SAPUserProfile.cooking_gain.
total(i)*Occupancy_Ratio_Z2;
        SAPUserProfile.cooking_gain.Z3value(i)=SAPUserProfile.cooking_gain.
total(i)*Occupancy_Ratio_Z3;
        SAPUserProfile.cooking_gain.Z4value(i)=SAPUserProfile.cooking_gain.
total(i)*Occupancy_Ratio_Z4;
        SAPUserProfile.cooking_gain.Z5value(i)=0;
    end
    case 'on'
```

```
    for i=1:25
        SAPUserProfile.cooking_gain.time(i)=month_cumulative_secs(i);
        SAPUserProfile.cooking_gain.total(i)=5*Occupancy_Total+23;
        SAPUserProfile.cooking_gain.Z1value(i)=SAPUserProfile.cooking_gain.
total(i)*Occupancy_Ratio_Z1;
        SAPUserProfile.cooking_gain.Z2value(i)=SAPUserProfile.cooking_gain.
total(i)*Occupancy_Ratio_Z2;
        SAPUserProfile.cooking_gain.Z3value(i)=SAPUserProfile.cooking_gain.
total(i)*Occupancy_Ratio_Z3;
        SAPUserProfile.cooking_gain.Z4value(i)=SAPUserProfile.cooking_gain.
total(i)*Occupancy_Ratio_Z4;
        SAPUserProfile.cooking_gain.Z5value(i)=0;
    end
end

if isrow(SAPUserProfile.cooking_gain.time)==1                  %convert to
column vector if required
    SAPUserProfile.cooking_gain.time=SAPUserProfile.cooking_gain.time';
    SAPUserProfile.cooking_gain.total=SAPUserProfile.cooking_gain.total';
    SAPUserProfile.cooking_gain.Z1value=SAPUserProfile.cooking_gain.Z1value
';
    SAPUserProfile.cooking_gain.Z2value=SAPUserProfile.cooking_gain.Z2value
';
    SAPUserProfile.cooking_gain.Z3value=SAPUserProfile.cooking_gain.Z3value
';
    SAPUserProfile.cooking_gain.Z4value=SAPUserProfile.cooking_gain.Z4value
';
    SAPUserProfile.cooking_gain.Z5value=SAPUserProfile.cooking_gain.Z5value
';
end


%% Losses
%losses associated with the internal gains, NOT the complete Building losse
s
for i=1:25
        SAPUserProfile.losses_int.time(i)=month_cumulative_secs(i);
        SAPUserProfile.losses_int.total(i)=-40*Occupancy_Total;
        SAPUserProfile.losses_int.Z1value(i)=-40*Occupancy_Z1;
        SAPUserProfile.losses_int.Z2value(i)=-40*Occupancy_Z2;
        SAPUserProfile.losses_int.Z3value(i)=-40*Occupancy_Z3;
        SAPUserProfile.losses_int.Z4value(i)=-40*Occupancy_Z4;
        SAPUserProfile.losses_int.Z5value(i)=0;
end

if isrow(SAPUserProfile.losses_int.time)==1
    SAPUserProfile.losses_int.time=SAPUserProfile.losses_int.time';
    SAPUserProfile.losses_int.total=SAPUserProfile.losses_int.total';
    SAPUserProfile.losses_int.Z1value=SAPUserProfile.losses_int.Z1value';
    SAPUserProfile.losses_int.Z2value=SAPUserProfile.losses_int.Z2value';
    SAPUserProfile.losses_int.Z3value=SAPUserProfile.losses_int.Z3value';
    SAPUserProfile.losses_int.Z4value=SAPUserProfile.losses_int.Z4value';
    SAPUserProfile.losses_int.Z5value=SAPUserProfile.losses_int.Z5value';
end


%% Electrical Appliance Gains
% Initial base value of Electrical Appliance Gains
% is adjusted in the model based on the monthly variations in day length
% etc
switch reduced_gain
```

```
    case 'off'
    appliance_gain_base=207.8*((TFA*Occupancy_Total)^0.4714);

    case 'on'
    appliance_gain_base=(207.8*(TFA*Occupancy_Total)^0.4714)*0.67;  %same a
s standard appliance gain but with 33% reduction
end

for j=1:25
    i=round(j/2);
        if i==13
         i=12;
        end
        SAPUserProfile.appliance_gain.time(j)=month_cumulative_secs(j);
        SAPUserProfile.appliance_gain.total(j)=appliance_gain_base*(1+0.157
*cos(2*pi*(i-
1.78)/12))*(month_days(i)/365)*(1000/(24*month_days(i)));
        appliance_gain_totalvalue=appliance_gain_base*(1+0.157*cos(2*pi*(i-
1.78)/12))*(month_days(i)/365)*(1000/(24*month_days(i)));
        SAPUserProfile.appliance_gain.Z1value(j)=appliance_gain_totalvalue*
Occupancy_Ratio_Z1;
        SAPUserProfile.appliance_gain.Z2value(j)=appliance_gain_totalvalue*
Occupancy_Ratio_Z2;
        SAPUserProfile.appliance_gain.Z3value(j)=appliance_gain_totalvalue*
Occupancy_Ratio_Z3;
        SAPUserProfile.appliance_gain.Z4value(j)=appliance_gain_totalvalue*
Occupancy_Ratio_Z4;
        SAPUserProfile.appliance_gain.Z5value(j)=0;
end

if isrow(SAPUserProfile.appliance_gain.time)==1
    SAPUserProfile.appliance_gain.time=SAPUserProfile.appliance_gain.time';
    SAPUserProfile.appliance_gain.total=SAPUserProfile.appliance_gain.total
';
    SAPUserProfile.appliance_gain.Z1value=SAPUserProfile.appliance_gain.Z1v
alue';
    SAPUserProfile.appliance_gain.Z2value=SAPUserProfile.appliance_gain.Z2v
alue';
    SAPUserProfile.appliance_gain.Z3value=SAPUserProfile.appliance_gain.Z3v
alue';
    SAPUserProfile.appliance_gain.Z4value=SAPUserProfile.appliance_gain.Z4v
alue';
    SAPUserProfile.appliance_gain.Z5value=SAPUserProfile.appliance_gain.Z5v
alue';
end

%%   Lighting Gains
%   Initial
% SAP standard Appendix L
lighting_energy_total=59.73*(TFA*Occupancy_Total)^0.4714;    % Base lighting
 load Appendix L Eqn L1
LE_correction1=1-
(0.5*light_LE);                                % Correction factor for low en
ergy lighting Appendix L Eqn L2

switch glazing_type                                            %Transmittance
 Factors from Table 6b
    case 'Single glazed'
        glass_transmittance=0.85;
    case 'Double glazed (air or argon filled)'
        glass_transmittance=0.76;
```

```
    case 'Double glazed (low-E, hard-coat)'
        glass_transmittance=0.72;
    case 'Double glazed (low-E, soft-coat)'
        glass_transmittance=0.63;
    case 'Window with secondary glazing'
        glass_transmittance=0.76;
    case 'Triple glazed (air or argon filled)'
        glass_transmittance=0.68;
    case 'Triple glazed (low-E, hard-coat)'
        glass_transmittance=0.64;
    case 'Triple glazed (low-E, soft-coat)'
        glass_transmittance=0.57;
end

switch frame_type                                            %Frame Factors
from Table 6c
    case {'Wood','PVC-U'}
        frame_factor=0.7;
    case {'Metal','Metal, thermal break'}
        frame_factor=0.8;
end

switch shading % Shading levels according Table 6d
    case 'Heavy/> 80%'
        light_access=0.3;
    case 'More than average/>60% - 80%'
        light_access=0.54;
    case 'Average or unknown/20% - 60%'
        light_access=0.77;
    case 'Very little/< 20%'
        light_access=1;
end

daylight_gain=(0.9*window_area*glass_transmittance*frame_factor*light_acces
s)/TFA;

if daylight_gain <=0.095
    LE_correction2=52.2*(daylight_gain^2)-
(9.94*daylight_gain)+1.433;    % Ref Eqn L3
else
    LE_correction2=0.96;                                            % Ref E
qn L4
end

% 0.4 reduction factor if 'reduced gains' is chosen
switch reduced_gain
    case 'on'
    lighting_energy_annual=lighting_energy_total*LE_correction1*LE_correcti
on2*0.4;
    case 'off'
    lighting_energy_annual=lighting_energy_total*LE_correction1*LE_correcti
on2;
end

% monthly distribution and conversion to watts
for j=1:25
    i=round(j/2);
     if i==13
         i=12;
     end
     SAPUserProfile.light_gain.time(j)=month_cumulative_secs(j);
```

```
     SAPUserProfile.light_gain.totalvalue(j)=lighting_energy_annual*(1+0.5*
cos(2*pi()*((i-0.2)/12)))*month_days(i)/365*(0.85*1000/(24*month_days(i)));
     light_gain_totalvalue=lighting_energy_annual*(1+0.5*cos(2*pi()*((i-
0.2)/12)))*month_days(i)/365*(0.85*1000/(24*month_days(i)));
     SAPUserProfile.light_gain.Z1value(j)=light_gain_totalvalue*Occupancy_R
atio_Z1;
     SAPUserProfile.light_gain.Z2value(j)=light_gain_totalvalue*Occupancy_R
atio_Z2;
     SAPUserProfile.light_gain.Z3value(j)=light_gain_totalvalue*Occupancy_R
atio_Z3;
     SAPUserProfile.light_gain.Z4value(j)=light_gain_totalvalue*Occupancy_R
atio_Z4;
     SAPUserProfile.light_gain.Z5value(j)=0;
end

if isrow(SAPUserProfile.light_gain.time)==1
    SAPUserProfile.light_gain.time=SAPUserProfile.light_gain.time';
    SAPUserProfile.light_gain.totalvalue=SAPUserProfile.light_gain.totalval
ue';
    SAPUserProfile.light_gain.Z1value=SAPUserProfile.light_gain.Z1value';
    SAPUserProfile.light_gain.Z2value=SAPUserProfile.light_gain.Z2value';
    SAPUserProfile.light_gain.Z3value=SAPUserProfile.light_gain.Z3value';
    SAPUserProfile.light_gain.Z4value=SAPUserProfile.light_gain.Z4value';
    SAPUserProfile.light_gain.Z5value=SAPUserProfile.light_gain.Z5value';
end

%%   Hot Water Gains
% Initial base value of Hot Water Gains
% is adjusted in the model based on the monthly variations in day length
% etc
% Reference Table 1b,c & d from SAP standard
DHW_monthly_factor=[1.1,1.06,1.02,0.98,0.94,0.90,0.90,0.94,0.98,1.02,1.06,1
.1]; %Ref Table 1c SAP Standard
DHW_deltaT=[41.2,41.4,40.1,37.6,36.4,33.9,30.4,33.4,33.5,36.3,39.4,39.9];
     %Ref Table 1d SAP Standard
DHW_day_volume_avg=(25*Occupancy_Total)+36;
     %Ref Table 1b SAP standard

DHW_day_volume=DHW_day_volume_avg.*DHW_monthly_factor;
     %monthly adjustment
DHW_energy_month=4.190.*DHW_day_volume.*month_days.*DHW_deltaT./3600;
      %Ref parameter (45) from SAP calculation sheet
DHW_dist_loss=DHW_energy_month.*0.15;
     %Ref parameter (46) from SAP calculation sheet

combi_loss_fu=ones(12,1);


combi_loss_fu=combi_loss_fu';

switch DHW_type                                                          %De
termine DHW system specific losses
    case 'combi';
        keep_hot=BTSL_Param(gcb,'keep_hot');
        switch keep_hot
            case 'Yes'
                DHW_loss_month=900.*month_days/365;                       %k
Wh Ref Table 3a NOTE!! Table 3b gives option to enter measured data

            case 'No'
```

```
                DHW_loss_month=600.*combi_loss_fu.*month_days./365;
% kWh Ref Table 3a NOTE!! Table 3b gives option to enter measured data
        end
    case 'storage combi'
        combi_tank_vol=str2double(BTSL_Param(gcb,'combi_tank_vol'));
        if combi_tank_vol<55
                DHW_loss_month=0;
        else
                DHW_loss_month=(600-(combi_tank_vol-
15)*15).*combi_loss_fu.*month_days/365;
        end
    case 'tank'
        DHW_loss_month=0; %  Placeholder
end

DHW_heatgain_month=zeros(12,1);
for i=1:12
DHW_heatgain_month(i)=0.25*(0.85*DHW_energy_month(i)+DHW_loss_month(i))+0.8
*DHW_dist_loss(i);  % in kW
end
DHW_heatgain_month=DHW_heatgain_month';

for j=1:25
    i=round(j/2);
   % transfer into struct for easy access from simulink model & convert to
Watts
     if i==13
         i=12;
     end
     SAPUserProfile.DHW_gain.time(j)=month_cumulative_secs(j);
     SAPUserProfile.DHW_gain.total(j)=1000*DHW_heatgain_month(i)/month_days
(i)/24;
     DHW_gain_totalvalue=1000*DHW_heatgain_month(i)/month_days(i)/24;
     SAPUserProfile.DHW_gain.Z1value(j)=DHW_gain_totalvalue*Occupancy_Ratio
_Z1;
     SAPUserProfile.DHW_gain.Z2value(j)=DHW_gain_totalvalue*Occupancy_Ratio
_Z2;
     SAPUserProfile.DHW_gain.Z3value(j)=DHW_gain_totalvalue*Occupancy_Ratio
_Z3;
     SAPUserProfile.DHW_gain.Z4value(j)=DHW_gain_totalvalue*Occupancy_Ratio
_Z4;
     SAPUserProfile.DHW_gain.Z5value(j)=0;
end

if isrow(SAPUserProfile.DHW_gain.time)==1
    SAPUserProfile.DHW_gain.time=SAPUserProfile.DHW_gain.time';
    SAPUserProfile.DHW_gain.total=SAPUserProfile.DHW_gain.total';
    SAPUserProfile.DHW_gain.Z1value=SAPUserProfile.DHW_gain.Z1value';
    SAPUserProfile.DHW_gain.Z2value=SAPUserProfile.DHW_gain.Z2value';
    SAPUserProfile.DHW_gain.Z3value=SAPUserProfile.DHW_gain.Z3value';
    SAPUserProfile.DHW_gain.Z4value=SAPUserProfile.DHW_gain.Z4value';
    SAPUserProfile.DHW_gain.Z5value=SAPUserProfile.DHW_gain.Z5value';
end


set_param(gcb,'Occupancy_Total',num2str(Occupancy_Total));
set_param(gcb,'Occupancy_Z1',num2str(Occupancy_Z1));
set_param(gcb,'Occupancy_Z2',num2str(Occupancy_Z2));
set_param(gcb,'Occupancy_Z3',num2str(Occupancy_Z3));
set_param(gcb,'Occupancy_Z4',num2str(Occupancy_Z4));
set_param(gcb,'Flag_TRV',num2str(Flag_TRV));
```

```
assignin('base','SAPUserProfile',SAPUserProfile);

clear all
```

9.5 Appendix E: Empirical data A Building and heating system plans

9.5.1 Boiler UK1

Product datasheet on energy consumption

Greenstar

42CDi Classic ErP

7738100246

The following product data complies with the requirements of EU Regulations 811/2013, 812/2013, 813/2013 and 814/2013 as supplement to the Directive 2010/30/EU.

Productdata	Symbol	Unit	7738100246
Condensing boiler			Yes
Combination heater			Yes
Rated heat output	Prated	kW	30
Seasonal space heating energy efficiency	η_s	%	92
Energy Efficiency Class			A
Useful heat output			
At rated heat output and high temperature regime	P_4	kW	30,0
At 30 % of rated heat output and low temperature regime	P_1	kW	10,0
Useful efficiency			
At rated heat output and high temperature regime	η_4	%	88,2
At 30 % of rated heat output and low temperature regime	η_1	%	97,5
Auxiliary electricity consumption			
At full load	elmax	kW	0,052
At part load	elmin	kW	0,028
In standby mode	P_{SB}	kW	0,004
Other items			
Standby heat loss	P_{stby}	kW	0,048
Ignition burner power consumption	P_{ign}	kW	0,000
Emissions of nitrogen oxides (only gas- or oil fired)	NO_x	mg/kWh	20
Sound power level, indoors	L_{WA}	dB	55
Additional data for combination heaters			
Declared load profile			XL
Water heating energy efficiency	η_{wh}	%	87
Water heating energy efficiency class			A
Daily electricity consumption (average climate conditions)	Q_{elec}	kWh	0,171
Annual electricity consumption	AEC	kWh	38
Daily fuel consumption	Q_{fuel}	kWh	22,377
Annual fuel consumption	AFC	GJ	18

WORCESTER

Worcester - Bosch Group - Cotswold Way - Warndon - Worcester WR4 9SW - UK

6720837928 (2015/07)

9.5.2 Boiler UK2

2.2 TECHNICAL DATA

DESCRIPTION		NATURAL GAS			LPG	
	UNIT	24i junior	Low NOx 24i & 28i junior	28i junior	24i junior	28i junior
Domestic Hot Water						
Minimum heat input	kW	7.00	Low NOx only applies to Central Heating	7.00	9.64	9.64
Maximum rated heat output	kW	24		28	24	28
Maximum rated heat input (net)	kW	24.49		28.57	24.49	28.57
Gas flow rate - Max. 10 minutes from lighting						
Natural Gas G20	m³/h	2.59		3.02	-	-
Propane Gas (LPG)	kg/h	-		-	1.9	2.22
Maximum mains inlet pressure	bar	10		10	10	10
Minimum mains inlet pressure (working) for max. flow	bar	1.3		1.3	1.3	1.3
Minimum mains inlet pressure (working) for operation	bar	0.2		0.2	0.2	0.2
Domestic Hot Water temperature setting	°C	55		55	55	55
Domestic Hot Water specific rate - 30 °C rise	l/min.	11.5		13.4	11.5	13.4
Max. Domestic Hot Water flow rate - 40 °C rise ± 15%	l/min.	8.6		10	8.6	10
Central Heating						
Maximum rated heat input (net)	kW	24.62	13.4	24.62	24.62	24.62
Maximum rated heat output 40/30 °C	kW	25.67	13.97	25.67	25.67	25.67
Maximum rated heat output 50/30 °C	kW	25.45	13.85	25.45	25.45	25.45
Maximum rated heat output 80/60 °C	kW	24	13	24	24	24
Maximum flow temperature	°C	82	82	82	82	82
Maximum permissible operating pressure	bar	2.5	2.5	2.5	2.5	2.5
Available pump head at 21 °C system temperature rise	m	2.0	2.0	2.0	2.0	2.0
Flue						
Flue gas temperature 80/60 °C, rated/min. load	°C	78/63	66/57	78/64	79/64	79/65
Flue gas temperature 40/30 °C, rated/min. load	°C	54/35	43/35	54/36	55/38	55/39
CO_2 level at max. rated heat output (after 30 minutes)	%	9.8	9.8	9.8	11.0	11.0
CO_2 level at min. rated heat output (after 30 minutes)	%	8.8	8.8	8.8	10.5	10.5
NOx class		5	5	5	5	5
NOx rating	mg/kWh	66	38	66	69	69
Condensate						
Maximum condensate rate	l/h	2.0	1.02	2.0	2.0	2.0
pH value, approx.		4.8	4.8	4.8	4.8	4.8
Electrical						
Electrical power supply voltage	a.c. V	230	230	230	230	230
Frequency	Hz	50	50	50	50	50
Maximum power consumption	W	140	140	140	140	140
General data						
SEDBUK	band	A	A	A	A	A
Appliance protection rating	IP	X4D	X4D	X4D	X4D	X4D
Appliance protection rating with mechanical or RF mechanical timer or FW100 module fitted	IP	20	20	20	20	20
Permissible ambient temperatures	°C	0 - 50	0 - 50	0 - 50	0 - 50	0 - 50
Nominal capacity of appliance	litre	3.9	3.9	3.9	3.9	3.9
Noise output level (Max central heating)	dBA	42	42	42	42	42
Total boiler weight	kg	37.5	37.5	37.5	37.5	37.5
Lift weight	kg	27.1	27.1	27.1	27.1	27.1
SEDBUK	%	90.1	90.1	90.1	91.8	91.8

Tab. 6 Technical data i Junior

9.5.3 Boiler UK3

APPLIANCE INFORMATION

WORCESTER
Bosch Group

3.2 TECHNICAL DATA

DESCRIPTION i System Compact	UNIT	Natural Gas 27kW	Natural Gas 30kW	L.P.G. 27kW	L.P.G. 30kW
Gas flow rate - Max. 10 minutes from lighting					
Natural Gas G20	m^3/h	2.92	3.24		
L.P.G.	kg/h			2.1	2.33
Heating					
Minimum heat input	kW	7.15	7.15	7.15	7.15
Maximum rated heat input (net)	kW	27.58	30.65	27.58	30.65
Maximum rated heat output 40/30°C	kW	28.55	31.70	28.55	31.70
Maximum rated heat output 50/30°C	kW	28.4	31.57	28.4	31.57
Maximum rated heat output 80/60°C	kW	27.0	30.0	27.0	30.0
Maximum flow temperature	°C	82	82	82	82
Maximum possible flow temperature	°C	86	86	86	86
Maximum permissible operating pressure	bar	2.5	2.5	2.5	2.5
Available pump head at 21°C system temperature rise	m	2.0	2.0	2.0	2.0
Flue					
Flue gas temperature 80/60°C, rated/min. load	°C	67/64	70/64	69/66	72/66
Flue gas temperature 40/30°C, rated/min. load	°C	48/36	50/36	50/37	52/37
CO_2 level at max. rated heat output (after 30 minutes)	%	9.1	9.1	10.6	10.6
CO_2 level at min. rated heat output (after 30 minutes)	%	8.5	8.5	9.6	9.6
NOx class		5	5	5	5
NOx rating	mg/kWh	35	35	40	42
Condensate					
Maximum condensate rate	l/h	2.5	2.5	2.5	2.5
pH value, approx.		4.8	4.8	4.8	4.8
Electrical					
Electrical power supply voltage	a.c. V	230	230	230	230
Frequency	Hz	50	50	50	50
Maximum power consumption - running	W	102	109	102	109
Maximum power consumption - stand-by	W	1	1	1	1
General data					
Appliance protection rating	IP	X4D	X4D	X4D	X4D
Appliance protection rating with FW100 module fitted*	IP	IP20	IP20	IP20	IP20
Appliance protection rating with Sense II module fitted*	IP	IPX2D	IPX2D	IPX2D	IPX2D
Permissible ambient temperatures	°C	0 - 50	0 - 50	0 - 50	0 - 50
Nominal capacity of appliance	litre	2.1	2.1	2.1	2.1
Total boiler weight	kg	37.5	37.5	37.5	37.5
Lift weight	kg	27.3	27.3	27.3	27.3
SEDBUK 2005	Band	A	A	A	A
SEDBUK 2009	%	89.0	89.0	90.0	90.0

Table 4 Technical data i System Compact

i * used with the optional integral diverter valve kit.

9.5.4 Boiler DE1

2.3 Produktdaten zum Energieverbrauch

Die folgenden Produktdaten entsprechen den Anforderungen der EU-Verordnungen Nr. 811/2013, 812/2013, 813/2013 und 814/2013 zur Ergänzung der Richtlinie 2010/30/EU.

Produktdaten	Symbol	Einheit	7 738 100 659	7 738 100 602	7 738 100 585
			7 738 100 660	7 738 100 651	7 738 100 658
Produkttyp	–	–	GB192-15 iT210SW H GB192-15 iT210S H	GB192-25 iT210SW H GB192-25 iT210S H	GB192-25 iT150W H (CH) GB192-25 iT150 H (CH)
Brennwertkessel	–	–	ja	ja	ja
Kombiheizgerät	–	–	ja	ja	ja
Nennwärmeleistung	P_{rated}	kW	15	25	25
Jahreszeitbedingte Raumheizungs-Energieeffizienz	η_s	%	93	94	94
Energieeffizienzklasse	–	–	A	A	A
Nutzbare Wärmeleistung					
Bei Nennwärmeleistung und Hochtemperaturbetrieb [1]	P_4	kW	14,7	24,5	24,5
Bei 30 % der Nennwärmeleistung und Niedertemperaturbetrieb [2]	P_1	kW	4,9	8,1	8,1
Wirkungsgrad					
Bei Nennwärmeleistung und Hochtemperaturbetrieb [1]	η_4	%	88,1	88,1	88,1
Bei 30 % der Nennwärmeleistung und Niedertemperaturbetrieb [2]	η_1	%	97,8	97,5	97,5
Hilfsstromverbrauch					
Bei Volllast	el_{max}	kW	0,020	0,040	0,040
Bei Teillast	el_{min}	kW	0,012	0,012	0,012
Im Bereitschaftszustand	P_{SB}	kW	0,001	0,001	0,001
Sonstige Angaben					
Wärmeverlust im Bereitschaftszustand	P_{stby}	kW	0,060	0,060	0,060
Stickoxidemission	NOx	mg/kWh	22	36	36
Schallleistungspegel in Innenräumen	L_{WA}	dB(A)	39	46	46
Zusätzliche Angaben für Kombiheizgeräte					
Angegebenes Lastprofil	–	–	XL	XL	XL
Täglicher Stromverbrauch	Q_{elec}	kWh	0,113	0,113	0,169
Jahresstromverbrauch	AEC	kWh	25	25	37
Täglicher Brennstoffverbrauch	Q_{fuel}	kWh	23,086	23,086	24,060
Jährlicher Brennstoffverbrauch	AFC	GJ	18	18	19
Warmwasserbereitungs-Energieeffizienz	η_{wh}	%	85	85	82
Warmwasserbereitungs-Energieeffizienzklasse	–	–	A	A	B
Warmhalteverlust	S	W	89	89	51
Speichervolumen	V	l	207	207	150
Nicht-solares Speichervolumen	Vbu	–	123	123	150
Speichertyp	–	–	DHW	DHW	DHW

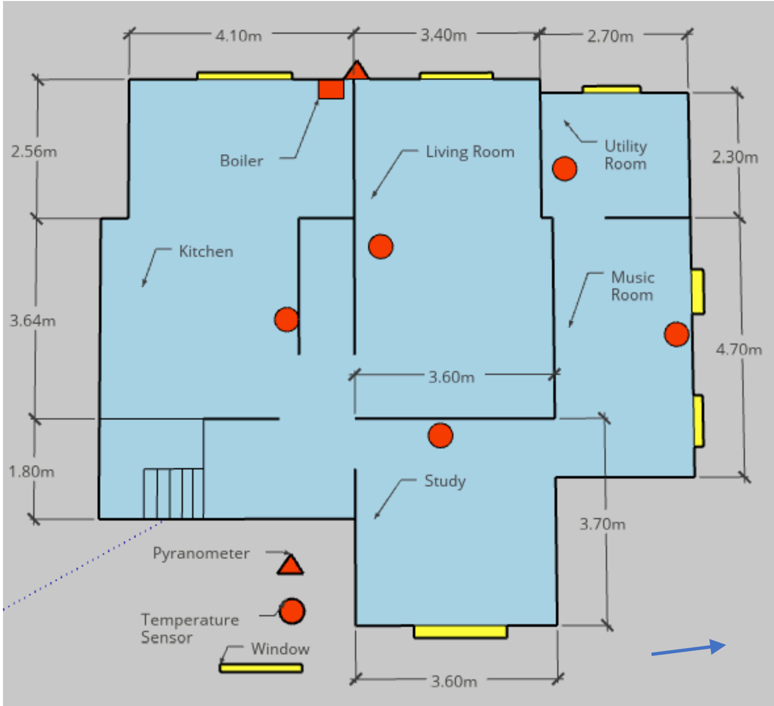
1) Hochtemperaturbetrieb bedeutet eine Rücklauftemperatur von 60 °C am Heizgeräteinlass und eine Vorlauftemperatur von 80 °C am Heizgerätauslass.

2) Niedertemperaturbetrieb bedeutet eine Rücklauftemperatur (am Heizgeräteinlass) für Brennwertkessel von 30 °C, für Niedertemperaturkessel von 37 °C und für andere Heizgeräte von 50 °C

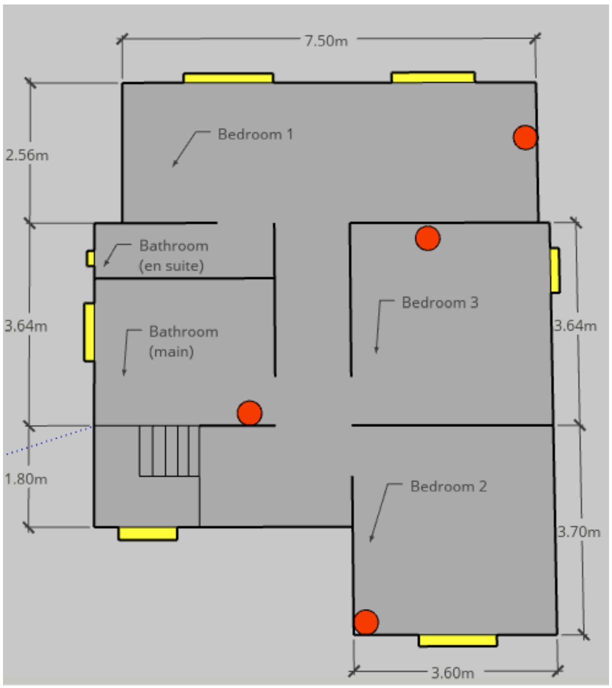
Tab. 4 Produktdaten zum Energieverbrauch

9.5.5 House UK1

Ground Floor and legend (not to scale)

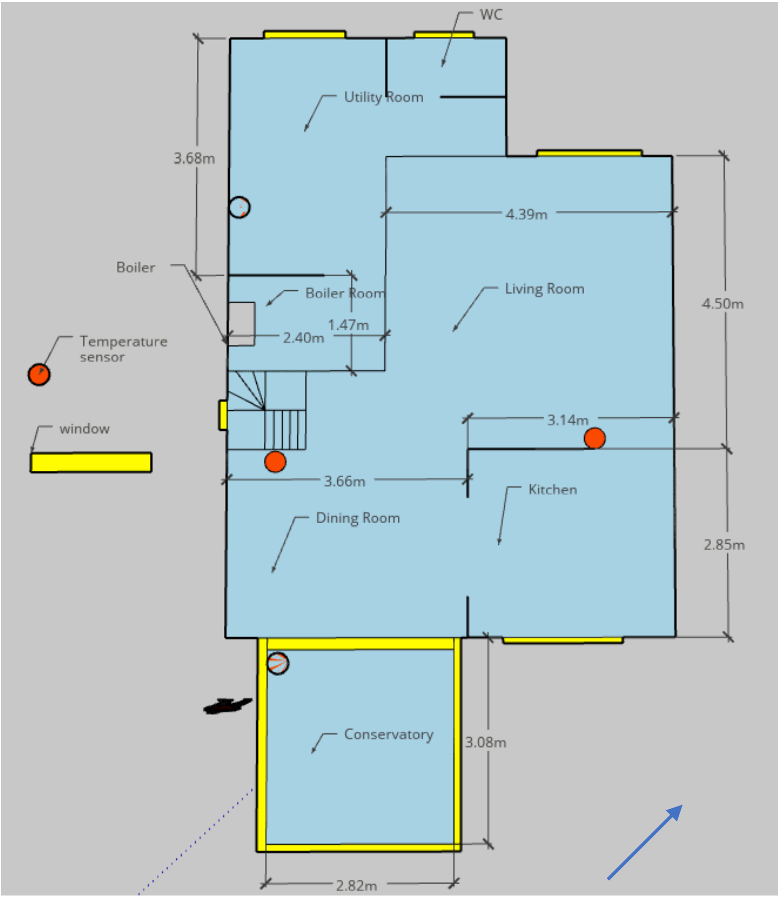


First floor (not to scale)

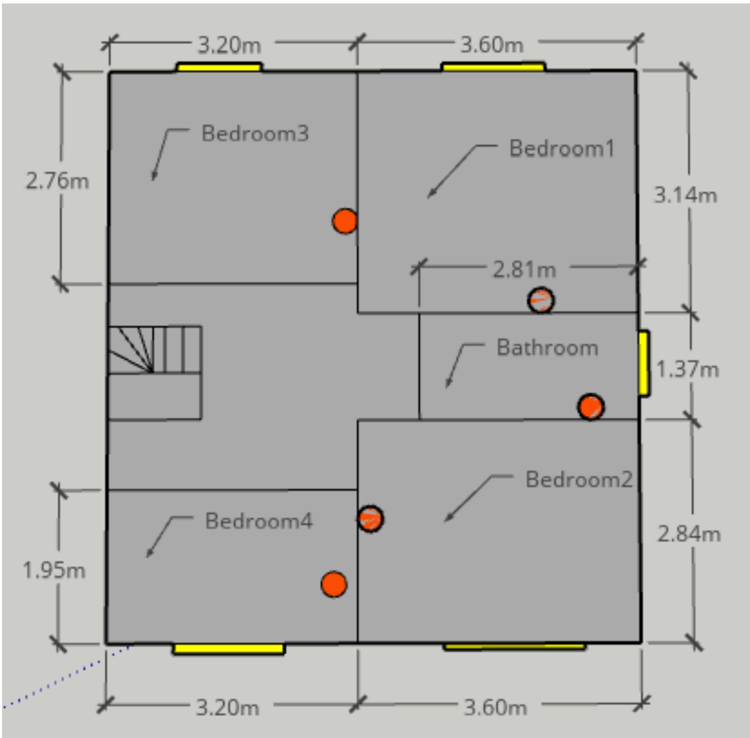


9.5.6 House UK2

Ground floor and legend (not to scale)

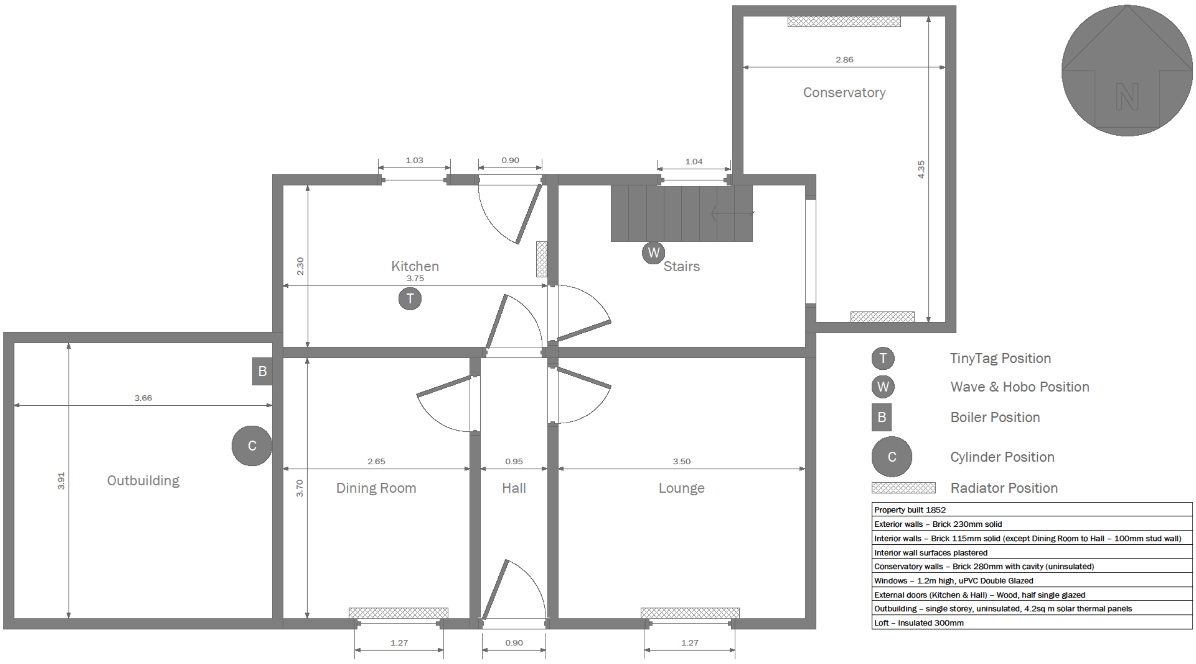


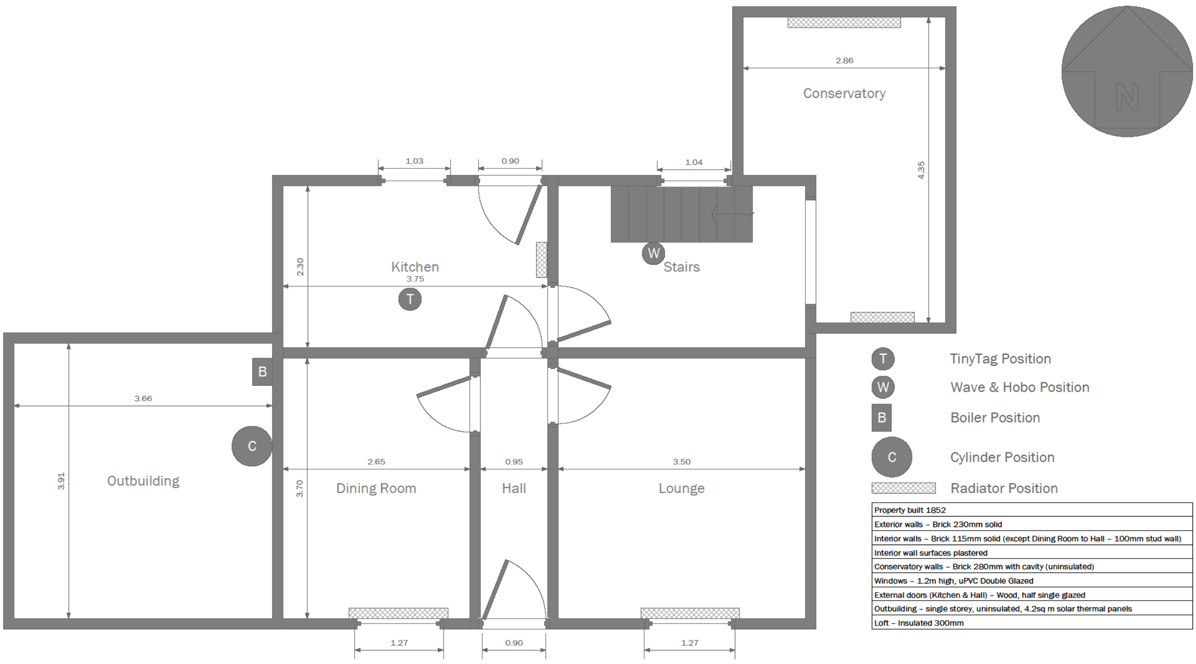
First floor (not to scale)



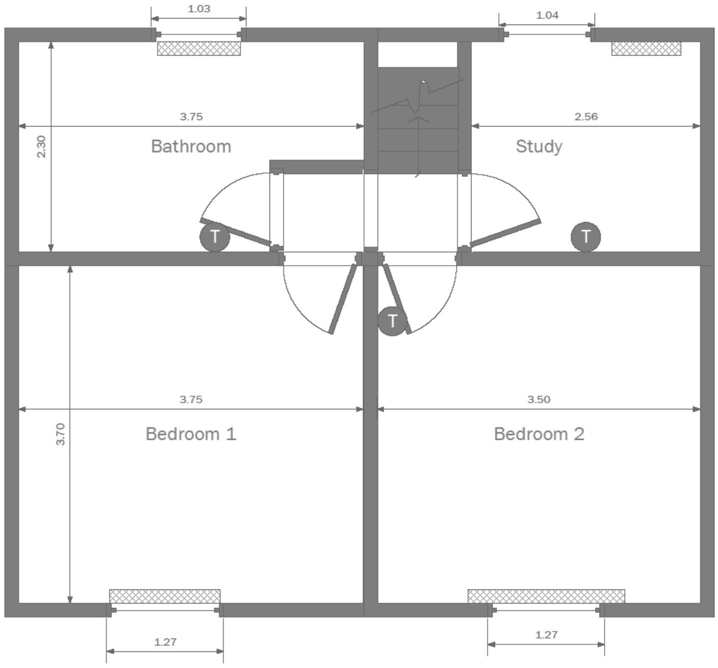
9.5.7 House UK3

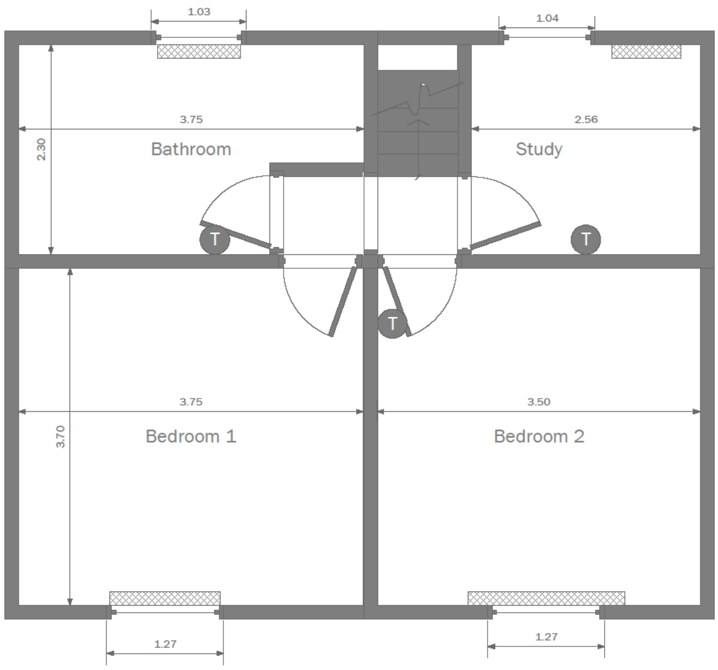
Ground Floor (not to scale)





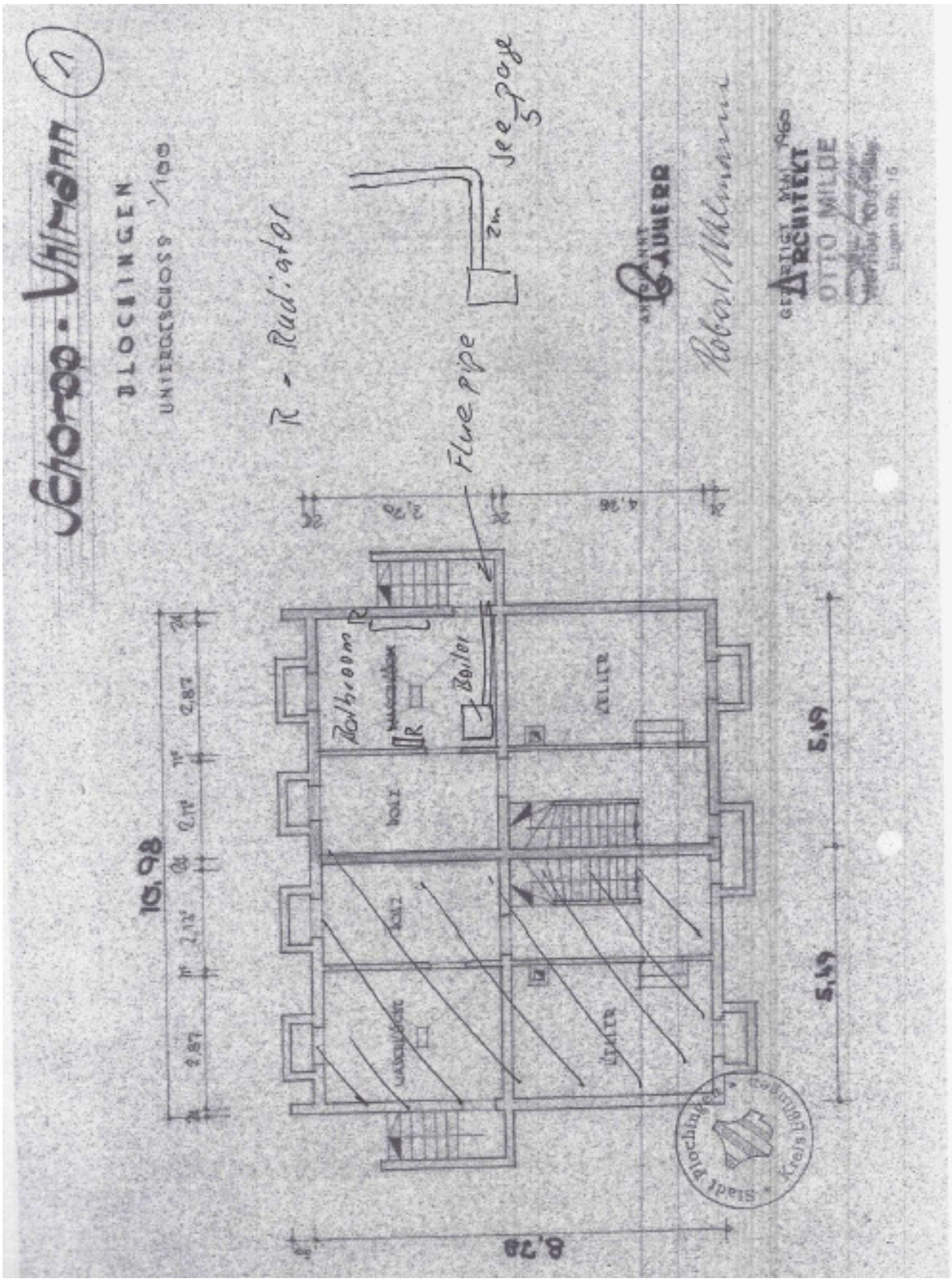
First floor (not to scale)



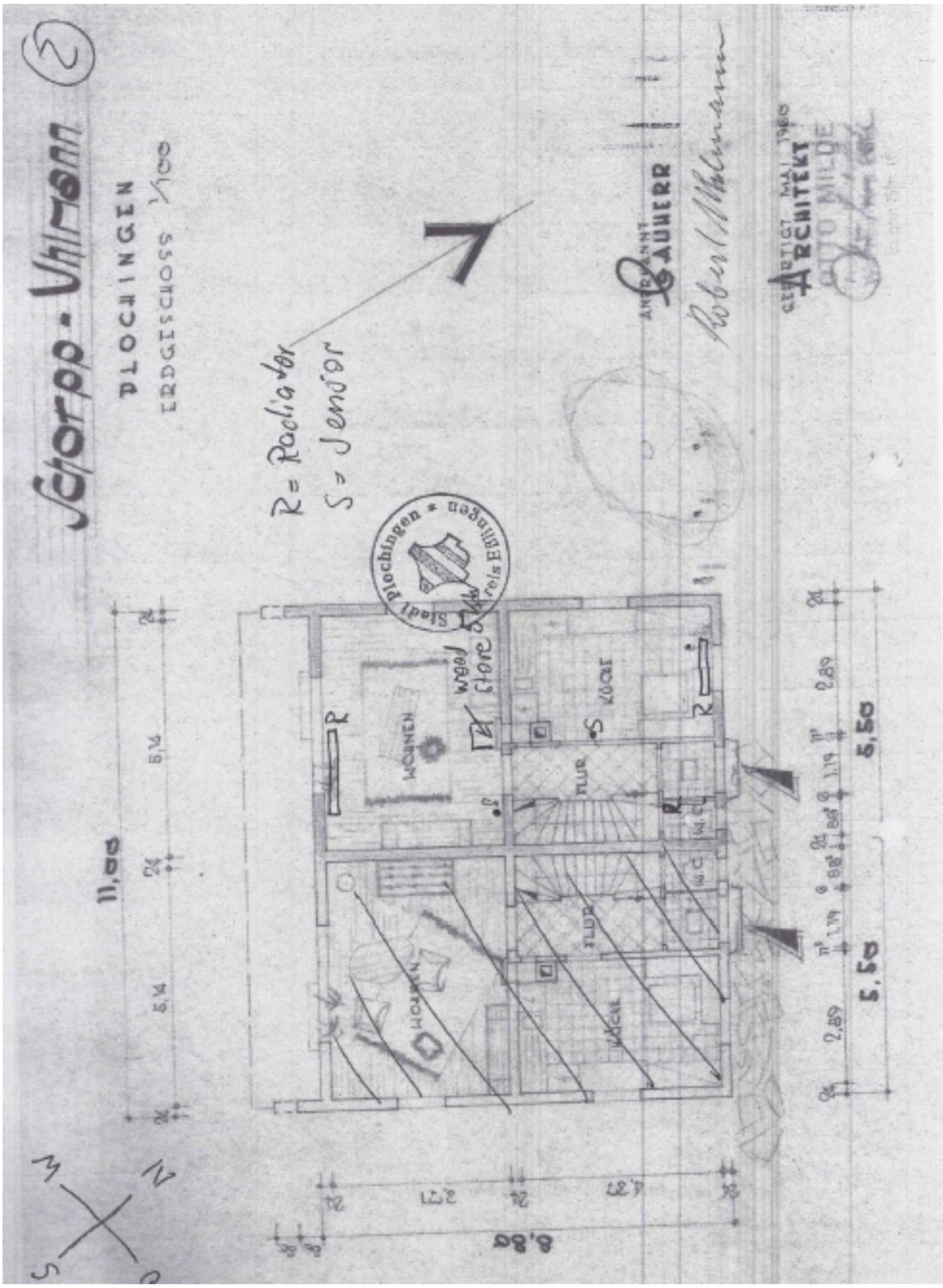


9.5.8 House DE1

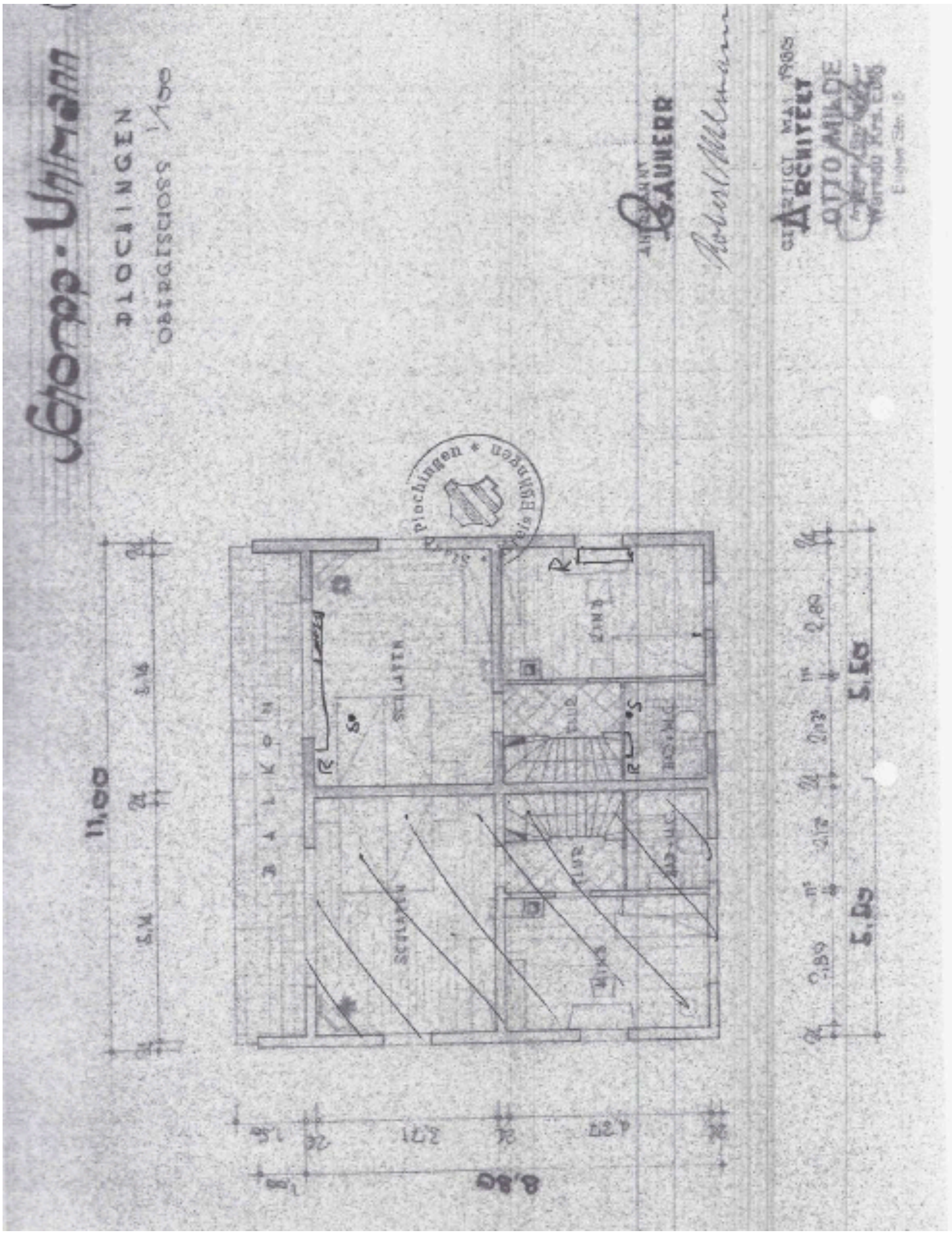
Basement



Ground floor

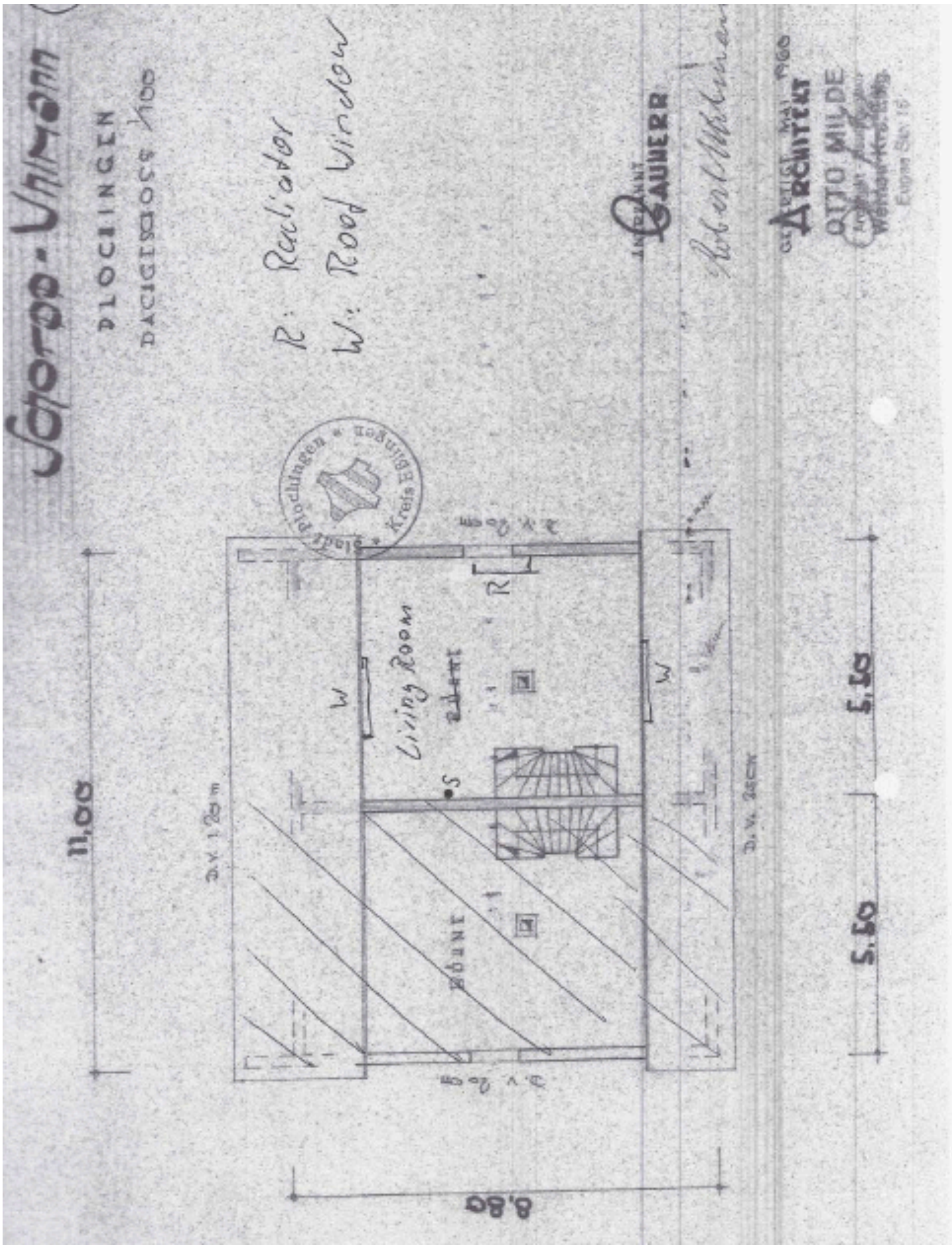


First floor

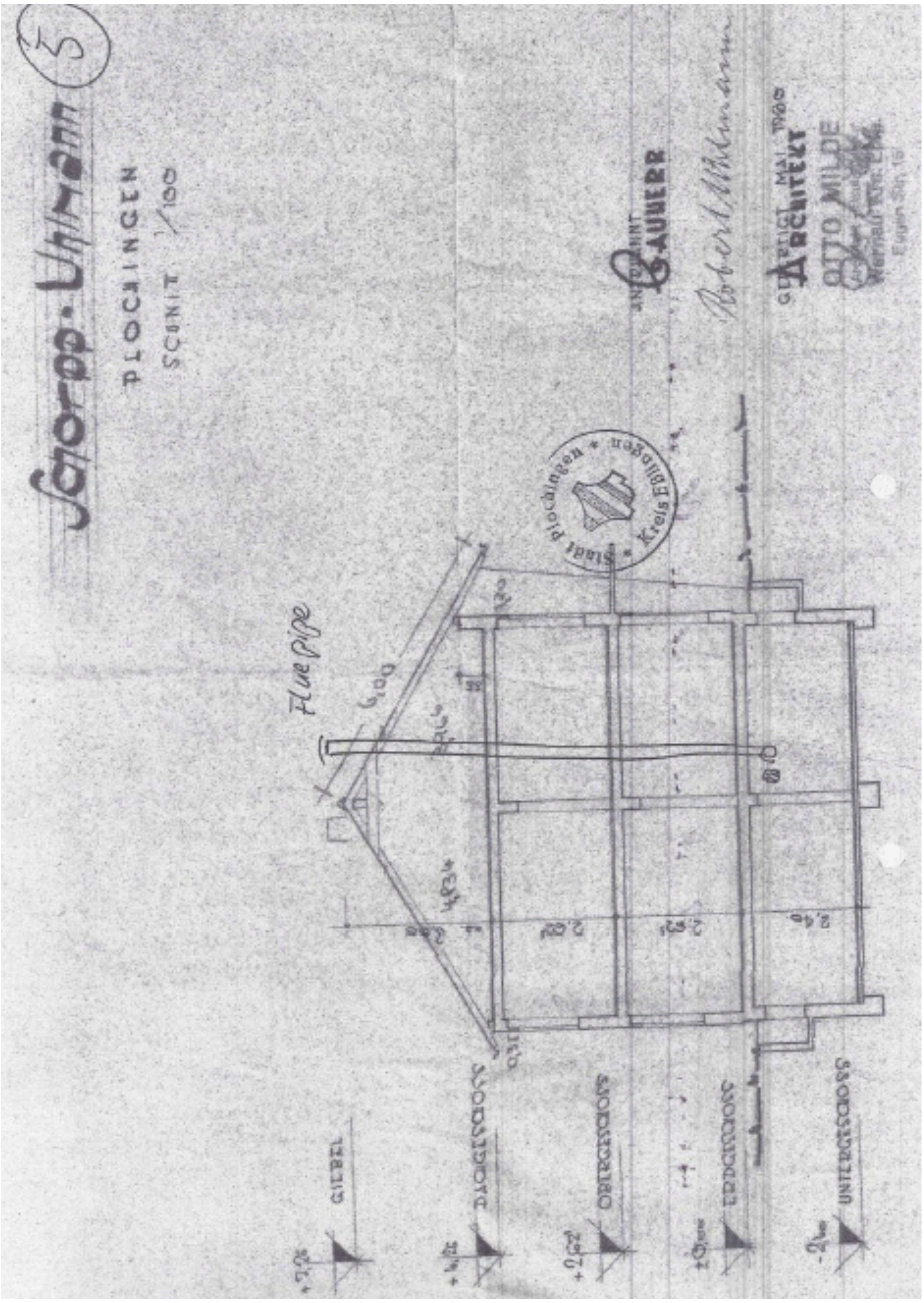


PLOCHINGEN
OBERGESCHOSS 1/100
BALKON
11,00
8,80
ARCHITEKT
OTTO WILDE

Second floor



Vertical elevation



9.6 Appendix F: Informed consent form

Research Study Information Sheet

You are being invited to take part in a research project. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. You will be given a copy of this information sheet.

Title of Project:	Comparison of the next generation of domestic heating solutions to identify the most appropriate solutions for real world conditions (working title)
Researcher's name:	George Bennett
Work address:	UCL Energy Institute, Central House, 14 Upper Woburn Place, London WC1H 0HY
Contact details:	

What is the purpose of this study?

My research investigates the in situ behaviour and performance of heating systems in UK homes. The process is described below.

What are the possible benefits of taking part?

By agreeing to allow this study to take place in your house, you will contribute towards knowledge of heating in homes and problems that can occur. An improvement in the quality and accuracy of the Energy Performance Certificates is a goals of the project as a whole.

Timing

This research will take place in your house from Q2 2015 to Q2 2017, which is referred to as the Research Period. The Research Period will be split into 3 parts as outlined below:

Part A: Installing monitoring equipment at the boiler and in rooms

- Time required: approximately 6 hours
- Date: Q2 2015

Part B: Visits by Researcher for the purposes of data collection

Time required: approximately 2 hour(s) per visit

- Timing:- visits every 3 months

Part C: Removing all equipment

- Time required: approximately 2 hours
- Date: Q2 2017

Description of work involved

Part A (Undertaken by Researcher and Homeowner, if a Worcester Bosch employee and under agreement with the Researcher)

1. Connection of 'Weblogger' unit to Boiler, including connection of wired thermocouples to boiler and outside wall.
2. Placement and setup of battery powered temperature sensors in most rooms.
3. Placement and connection of 'Loop' gas and electric meter measurement devices. (If agreed with homeowner)
4. Placement and connection of Pyranometer (outdoor solar radiation sensor) (If agreed with homeowner)

Part B (Undertaken by Researcher and Homeowner, if a Worcester Bosch employee and under agreement with the Researcher)

Visit to home approx. every 3 months by researcher to download temperature sensor data.

Part C (Undertaken by Researcher and Homeowner, if a Worcester Bosch employee and under agreement with the Researcher)

All equipment will be removed, and the areas affected by the research fully returned to their original condition by the end of the Research Period.

Access

1. Access will be required on a 3 month basis in order to download the temperature sensor data, although this can be done by the homeowner with prior agreement and training from the researcher
2. In the event of a failure in the online monitoring equipment (Weblogger or Loop) then access may be required if a remote solution cannot be found.
3. If a problem of the type described in 2 cannot be resolved then access to the equipment by a third party from Worcester Bosch may be required.

Privacy

4. Photographs will be taken of the locations of the sensor equipment, but will never show any personal or private effects or any objects or identifiable property. Access to images can be obtained at any time and you have the right to ask for any to be deleted.

What else?

☐ **Your participation is voluntary and you have the right to withdraw at any time**

☐ Any information obtained will be anonymous and is just for research purposes.

☐ If you decide to take part you will be given this information sheet to keep and be asked to sign a consent form.

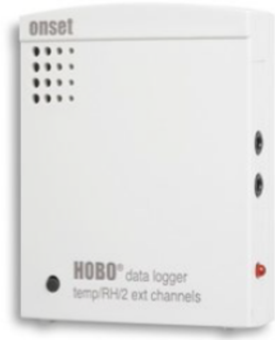
☐ Please discuss the information above with others if you wish or ask the Researcher if there is anything that is not clear or if you would like more information.

☐ It is up to you to decide whether to take part or not; choosing not to take part will not disadvantage you in any way. If you do decide to take part you are still free to withdraw at any time and without giving a reason.

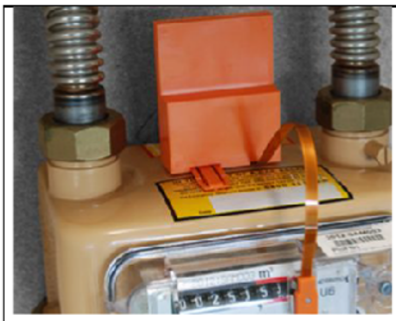
Monitoring equipment example images

Weblogger

Tinytag/HOBO Temperature Sensors

 Dimensions: 60.2mm diameter x 15.3mm thick	 Dimensions: 58mm x 74mm x 22mm

Loop Meter sensors

Informed consent form for participants in research studies

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Project: Comparison of the next generation of domestic heating solutions to identify the most appropriate solutions for real world conditions

Researcher's name: George Bennett

Work address: UCL Energy Institute, Central House, 14 Upper Woburn Place, London WC1H 0HY

Contact details: [illegible]

Thank you for your interest in taking part in this research. Before you agree to take part, the person organising the research must explain the project to you. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the Researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

Participant's Statement

1. I confirm that I have read the notes written above and the Information Sheet, and understand what the study involves. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. If I have further queries about the study, I know I can get in touch with the Researchers through the above contact details.
2. I understand that my participation in the study is entirely voluntary and that if I decide at any time that I no longer wish to take part in this project, I can notify the Researcher and withdraw immediately, without giving reason. In the event that I withdraw from the study, any collected data will be kept by the Researcher, and associated analysis will still be made. I will allow the Researcher to come and collect any dataloggers/instruments in my property, which remain property of the Researcher / Worcester Bosch / UCL at all times.
3. I hereby agree to participate in the research study, which involves the Researcher undertaking the monitoring from Q2 2015 to no later than Aug 2017.
4. No personal data will be collected and any collected non-personal data will be anonymised and treated as confidential.
5. I understand that the information collected will be used and retained for the length of the study and beyond this (see point 6) and I can have access to the findings as described in the information sheet.
6. I agree that the data collected may be used by other UCL / Worcester Bosch Researchers for future research beyond the length of the study or the Researcher's study time. I am assured that confidentiality will be upheld.
7. I understand that the data collected belongs to the project and that this information can be used by the Researcher in presentations and publications and I can obtain a copy upon request. Confidentiality and anonymity will be maintained and it will not be possible to identify me from any publications.
8. I understand that digital photos may be taken of the internal and external surface of the wall, surrounding floor and wall surfaces, as well as cable routes back into the house, but will never show any personal or private effects or any objects or identifiable property. I understand that I can obtain access to any images at any time and that I have the right to ask any to be deleted.
9. I agree that the research project named above has been explained to me to my satisfaction and I agree to take part in this study

Name of participant: Signed: Date:

Name of Researcher: Signed: Date:

9.6.1 Appendix D: Informed consent form UK1

Informed consent form for participants in research studies

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Project: Comparison of the next generation of domestic heating solutions to identify the most appropriate solutions for real world conditions

Researcher's name: George Bennett

Work address: UCL Energy Institute, Central House, 14 Upper Woburn Place, London WC1H 0HY

Contact details: [illegible]

Thank you for your interest in taking part in this research. Before you agree to take part, the person organising the research must explain the project to you. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the Researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

Participant's Statement

1. I confirm that I have read the notes written above and the Information Sheet, and understand what the study involves. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. If I have further queries about the study, I know I can get in touch with the Researchers through the above contact details.
2. I understand that my participation in the study is entirely voluntary and that if I decide at any time that I no longer wish to take part in this project, I can notify the Researcher and withdraw immediately, without giving reason. In the event that I withdraw from the study, any collected data will be kept by the Researcher, and associated analysis will still be made. I will allow the Researcher to come and collect any dataloggers/instruments in my property, which remain property of the Researcher / Worcester Bosch / UCL at all times.
3. I hereby agree to participate in the research study, which involves the Researcher undertaking the monitoring from Q2 2015 to no later than Aug 2017.
4. No personal data will be collected and any collected non-personal data will be anonymised and treated as confidential.
5. I understand that the information collected will be used and retained for the length of the study and beyond this (see point 6) and I can have access to the findings as described in the information sheet.
6. I agree that the data collected may be used by other UCL / Worcester Bosch Researchers for future research beyond the length of the study or the Researcher's study time. I am assured that confidentiality will be upheld.
7. I understand that the data collected belongs to the project and that this information can be used by the Researcher in presentations and publications and I can obtain a copy upon request. Confidentiality and anonymity will be maintained and it will not be possible to identify me from any publications.
8. I understand that digital photos may be taken of the internal and external surface of the wall, surrounding floor and wall surfaces, as well as cable routes back into the house, but will never show any personal or private effects or any objects or identifiable property. I understand that I can obtain access to any images at any time and that I have the right to ask any to be deleted.
9. I agree that the research project named above has been explained to me to my satisfaction and I agree to take part in this study

Name of participant: Signed: Date: 15th March 2015

[illegible]

Name of Researcher: Signed: Date:

GEORGE BENNETT [illegible] 15/3/2015

9.6.2 Appendix D: Informed consent form UK2

Informed consent form for participants in research studies

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Project: Comparison of the next generation of domestic heating solutions to identify the most appropriate solutions for real world conditions

Researcher's name: George Bennett

Work address: UCL Energy Institute, Central House, 14 Upper Woburn Place, London WC1H 0HY

Contact details: [illegible]

Thank you for your interest in taking part in this research. Before you agree to take part, the person organising the research must explain the project to you. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the Researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

Participant's Statement

1. I confirm that I have read the notes written above and the Information Sheet, and understand what the study involves. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. If I have further queries about the study, I know I can get in touch with the Researchers through the above contact details.
2. I understand that my participation in the study is entirely voluntary and that if I decide at any time that I no longer wish to take part in this project, I can notify the Researcher and withdraw immediately, without giving reason. In the event that I withdraw from the study, any collected data will be kept by the Researcher, and associated analysis will still be made. I will allow the Researcher to come and collect any dataloggers/instruments in my property, which remain property of the Researcher / Worcester Bosch / UCL at all times.
3. I hereby agree to participate in the research study, which involves the Researcher undertaking the monitoring from Q2 2015 to no later than Aug 2017.
4. No personal data will be collected and any collected non-personal data will be anonymised and treated as confidential.
5. I understand that the information collected will be used and retained for the length of the study and beyond this (see point 6) and I can have access to the findings as described in the information sheet.
6. I agree that the data collected may be used by other UCL / Worcester Bosch Researchers for future research beyond the length of the study or the Researcher's study time. I am assured that confidentiality will be upheld.
7. I understand that the data collected belongs to the project and that this information can be used by the Researcher in presentations and publications and I can obtain a copy upon request. Confidentiality and anonymity will be maintained and it will not be possible to identify me from any publications.
8. I understand that digital photos may be taken of the internal and external surface of the wall, surrounding floor and wall surfaces, as well as cable routes back into the house, but will never show any personal or private effects or any objects or identifiable property. I understand that I can obtain access to any images at any time and that I have the right to ask any to be deleted.
9. I agree that the research project named above has been explained to me to my satisfaction and I agree to take part in this study

Name of participant: Signed: Date:

Name of Researcher: Signed: Date:

GEORGE BENNETT 2. 3. 2015

George Bennett Information Sheet and Consent Form Page 5 of 5

9.6.3 Appendix D: Informed consent form UK3

Informed consent form for participants in research studies

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Project: Comparison of the next generation of domestic heating solutions to identify the most appropriate solutions for real world conditions

Researcher's name: George Bennett

Work address: UCL Energy Institute, Central House, 14 Upper Woburn Place, London WC1H 0HY

Contact details: [illegible] email: [illegible]

Thank you for your interest in taking part in this research. Before you agree to take part, the person organising the research must explain the project to you. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the Researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

Participant's Statement

1. I confirm that I have read the notes written above and the Information Sheet, and understand what the study involves. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. If I have further queries about the study, I know I can get in touch with the Researchers through the above contact details.
2. I understand that my participation in the study is entirely voluntary and that if I decide at any time that I no longer wish to take part in this project, I can notify the Researcher and withdraw immediately, without giving reason. In the event that I withdraw from the study, any collected data will be kept by the Researcher, and associated analysis will still be made. I will allow the Researcher to come and collect any dataloggers/instruments in my property, which remain property of the Researcher / Worcester Bosch / UCL at all times.
3. I hereby agree to participate in the research study, which involves the Researcher undertaking the monitoring from Q2 2015 to no later than Aug 2017.
4. No personal data will be collected and any collected non-personal data will be anonymised and treated as confidential.
5. I understand that the information collected will be used and retained for the length of the study and beyond this (see point 6) and I can have access to the findings as described in the information sheet.
6. I agree that the data collected may be used by other UCL / Worcester Bosch Researchers for future research beyond the length of the study or the Researcher's study time. I am assured that confidentiality will be upheld.
7. I understand that the data collected belongs to the project and that this information can be used by the Researcher in presentations and publications and I can obtain a copy upon request. Confidentiality and anonymity will be maintained and it will not be possible to identify me from any publications.
8. I understand that digital photos may be taken of the internal and external surface of the wall, surrounding floor and wall surfaces, as well as cable routes back into the house, but will never show any personal or private effects or any objects or identifiable property. I understand that I can obtain access to any images at any time and that I have the right to ask any to be deleted.
9. I agree that the research project named above has been explained to me to my satisfaction and I agree to take part in this study

Name of participant: Signed: Date:

[illegible]

Name of Researcher: Signed: Date:

GEORGE BENNETT [illegible] – 02/03/2015

George Bennett [illegible] Page 5 of 5

9.6.4 Appendix D: Informed consent form DE1

Informed consent form for participants in research studies

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Project:	Comparison of the next generation of domestic heating solutions to identify the most appropriate solutions for real world conditions
Researcher's name:	George Bennett
Work address:	UCL Energy Institute, Central House, 14 Upper Woburn Place, London WC1H 0HY
Contact details:	[illegible]

Thank you for your interest in taking part in this research. Before you agree to take part, the person organising the research must explain the project to you. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the Researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

Participant's Statement

1. I confirm that I have read the notes written above and the Information Sheet, and understand what the study involves. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. If I have further queries about the study, I know I can get in touch with the Researchers through the above contact details.
2. I understand that my participation in the study is entirely voluntary and that if I decide at any time that I no longer wish to take part in this project, I can notify the Researcher and withdraw immediately, without giving reason. In the event that I withdraw from the study, any collected data will be kept by the Researcher, and associated analysis will still be made. I will allow the Researcher to come and collect any dataloggers/instruments in my property, which remain property of the Researcher / Worcester Bosch / UCL at all times.
3. I hereby agree to participate in the research study, which involves the Researcher undertaking the monitoring from Q2 2015 to no later than Aug 2017.
4. No personal data will be collected and any collected non-personal data will be anonymised and treated as confidential.
5. I understand that the information collected will be used and retained for the length of the study and beyond this (see point 6) and I can have access to the findings as described in the information sheet.
6. I agree that the data collected may be used by other UCL / Worcester Bosch Researchers for future research beyond the length of the study or the Researcher's study time. I am assured that confidentiality will be upheld.
7. I understand that the data collected belongs to the project and that this information can be used by the Researcher in presentations and publications and I can obtain a copy upon request. Confidentiality and anonymity will be maintained and it will not be possible to identify me from any publications.
8. I understand that digital photos may be taken of the internal and external surface of the wall, surrounding floor and wall surfaces, as well as cable routes back into the house, but will never show any personal or private effects or any objects or identifiable property. I understand that I can obtain access to any images at any time and that I have the right to ask any to be deleted.
9. I agree that the research project named above has been explained to me to my satisfaction and I agree to take part in this study

Name of participant: Signed: Date:

[illegible]

Name of Researcher: Signed: Date:

GEORGE BENNETT 13.6.2016